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Review article

Berth allocation and scheduling at marine container terminals: A state-of-the-art review of solution approaches and relevant scheduling attributes

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Abstract

Marine container terminals play a significant role for international trade networks and global market. To cope with the rapid and steady growth of the seaborne trade market, marine container terminal operators must address the operational challenges with appropriate analytical methods to meet the needs of the market. The berth allocation and scheduling problem is one of the important decisions faced by operators during operations planning. The optimization of a berth schedule is strongly associated with the allocation of spatial and temporal resources. An optimal and robust berth schedule remarkably improves the productivity and competitiveness of a seaport. A significant number of berth allocation and scheduling studies have been conducted over the last years. Thus, there is an existing need for a comprehensive and critical literature survey to analyze the state-of-the-art research progress, developing tendencies, current shortcomings, and potential future research directions. Therefore, this study thoroughly selected scientific manuscripts dedicated to the berth allocation and scheduling problem. The identified studies were categorized based on spatial attributes, including discrete, continuous, and hybrid berth allocation and scheduling problems. A detailed review was performed for the identified study categories. A representative mathematical formulation for each category was presented along with a detailed summary of various considerations and characteristics of every study. A specific emphasis was given to the solution methods adopted. The current research shortcomings and important research needs were outlined based on the review of the state-of-the-art. This study was conducted with the expectation of assisting the scientific community and relevant stakeholders with berth allocation and scheduling.

Keywords: maritime transportation, marine container terminals, container terminal operations, berth allocation, berth scheduling, literature survey

1. Introduction

Maritime transportation is the most influential support for economic growth and globalization, dominating international trade with large volumes of cargo (Elmi *et al.*, 2022). According to the statistics collected for international commercial exchange, seaborne trade has been the most significant mode of international transportation for decades. Maritime transport handles more than 80% of worldwide trade, and for the most of developing nations, this share can be even greater. According to the figures reported by the United Nations Conference on Trade and Development, the amount of seaborne trade has been rising by 3% per year over the last four decades (UNCTAD, 2022). Marine container terminals (MCTs) are important transshipment centers in supply chains owing to their function of delivering or receiving containers to or from ships between various liner shipping companies and MCT operators. The increasing volume of maritime transportation has resulted in several challenges for MCT operators, such as congestion at ports, allocation of mega container ships, and ship service efficiency (Kumawat & Roy, 2021). To cope with the rapid and steady growth of the seaborne trade market, MCT operators must address the operational challenges with appropriate analytical methods to meet the needs of the market (Moon, 2000).

With the objective to maintain customer satisfaction and increase port productivity, MCT operators must make an effective use of their handling resources and berthing positions (Carlo *et al.*, 2015). The implementation of an optimized berth scheme typically results in higher profitability and competitiveness against other marine terminals. The optimization of a berth schedule is strongly associated with the planning of spatial and temporal resources. When arriving at an MCT, container ships normally wait for the scheduled berthing position that would be available and suitable for the terminal operation (Cordeau *et al.*, 2005). Berth allocation and scheduling decisions can be foreseen to be a challenging issue, which must be addressed by MCT operators with priority, since these decisions significantly affect how port equipment should be deployed and how storage spaces would be allocated (Xu *et al.*, 2012). A group of arriving ships are designated to be served within a specific planning horizon in a berth

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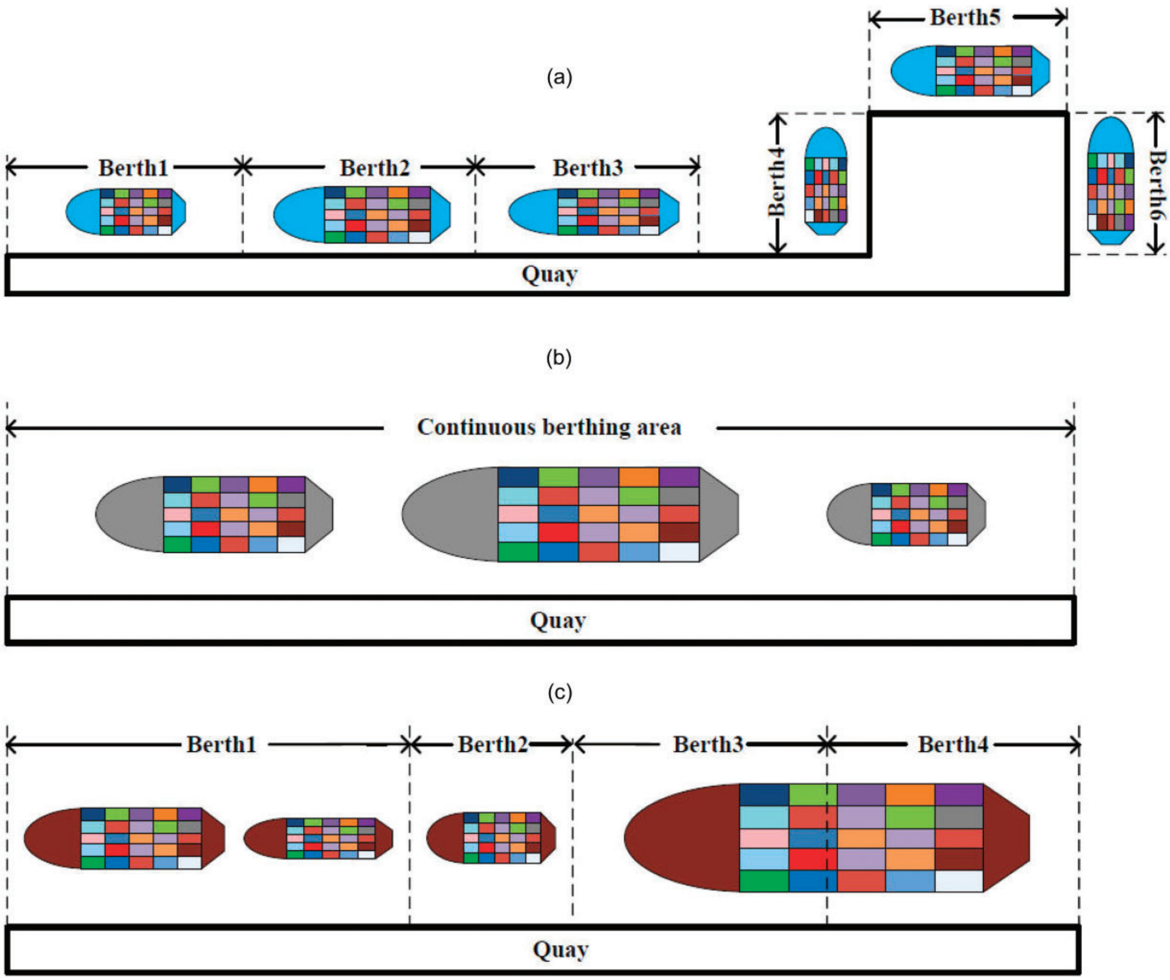

Figure 1: Differentiation of berthing layouts: (a) discrete berthing layout, (b) continuous berthing layout, and (c) hybrid berthing layout.

allocation and scheduling problem (BASP), and the configuration of the berth is predetermined. The allotted berthing position is the operating range of the allocated quay cranes, and the same equipment and berthing space generally cannot be simultaneously assigned to more than one ship. The direct research objective of BASPs is to provide a service schedule for each arriving ship with the optimal berthing position and timing, while avoiding conflicts with all practical limitations (Bierwirth & Meisel, 2010, 2015).

According to the spatial characteristics of the wharves at ports, the BASPs may generally be divided into three categories, which are discrete berth allocation and scheduling problems (DBASPs), continuous berth allocation and scheduling problems (CBASPs), and hybrid berth allocation and scheduling problems (HBASPs) (Bierwirth & Meisel, 2015). A wharf (or a quay) is separated into several distinct berthing segments in a DBASP. Within the specified physical constraints, a ship could moor and be handled by port equipment, and each allocated service position may only accommodate one ship at any time, as showcased in Fig. 1a. Different from the DBASP, a ship may moor anywhere along the designated wharf in a CBASP. The berthing space is assigned depending on the unique requirements rather than being separated into different berthing segments in advance. It is always defined as a default condition that the total length of ships to be serviced cannot be greater than the length of the wharf, as illustrated in Fig. 1b. A hybrid scenario is the one in which the wharf is pre-separated into sets of distinct berthing positions, yet a single ship could berth within more than one segment or may be authorized to utilize a berthing segment at the same time with other ships currently in operation (Cheong *et al.*, 2010). A classical illustration of a hybrid wharf is shown in Fig. 1c. Under all these three situations, the draft of the ship should be less than the allowable water depth of the berthing positions and access channel of the port (Carlo *et al.*, 2015).

In addition to the three primary classification categories based on spatial attributes, there are other special cases, such as the indented berthing layout adopted by Amsterdam Container Terminals (the Netherlands), where the ships berth inside the covered area of the wharf, allowing the equipment to work simultaneously on the two sides of the ships (Imai *et al.*, 2007). The channel berthing layout, where ships are moored and served along the channel, can be efficient for the service of mega container ships (Imai *et al.*, 2013). Furthermore, in some scenarios, the water depth of a specific port and access channel may fluctuate due to the tidal effects throughout the day and may not be adequate for the draft of a mega ship. Therefore, a number of studies have also included the draft of the scheduled ships as a spatial constraint and considered the impacts of tidal effects in the BASP (Dadashi *et al.*, 2017). BASPs could be classified into various groups based on the assumptions of the studies. For example, based on the anticipated arrival times of ships, BASPs can be classified as static problems or dynamic problems or stochastic problems. In case of static arrivals, ships are assumed to be at the port and ready for service. As for the dynamic arrival case, some ships may not be at the port yet, but their anticipated arrival time is known. In case of stochastic ship arrivals, ship arrivals are subject to uncertainty due to various disruptive events. According to the anticipated variability in handling times, relevant studies can be categorized into the studies assuming fixed handling time or the studies assuming variable handling time or the studies assuming uncertain handling time due to unforeseen events.

Uncertainties in ship arrivals and handling times can be caused by natural phenomena, such as hurricanes and tidal constraints, as well as human-related events, such as port congestion and handling equipment breakdowns (Lau *et al.*, 2022; Mansouri *et al.*, 2009). Considering the negative impacts of climate change, more and more BASP studies focus on environmental concerns to improve energy efficiency throughout container handling and decrease the amount of emissions produced (Budiyanto *et al.*, 2021). To cope with the growing demand for maritime transportation and reduce MCT congestion, different studies have been conducted suggesting promising alternatives, such as automation applications at seaports, changing tendencies of operational regulations and laws, and unique design of quay wharves, which should be investigated by the relevant stakeholders more in-depth (Emde *et al.*, 2014; Mi *et al.*, 2021; Torbitt & Hildreth, 2010).

A remarkable number of BASP research efforts bring the need to review and summarize the previously published studies and perform a detailed state-of-the-art analysis to determine the current trends and critical future research directions. Although a significant number of literature surveys were conducted on different aspects of maritime transportation and liner shipping (Christiansen *et al.*, 2020; Dulebenets *et al.*, 2021; Meng *et al.*, 2014, 2019; Pantuso *et al.*, 2014; Song, 2021; Wang & Meng, 2017), only several studies specifically concentrated on a comprehensive review of the BASP studies. Bierwirth and Meisel (2010) conducted a detailed review of the studies on berth allocation and quay crane scheduling at MCTs. The collected studies were classified based on different attributes, including the spatial attribute, temporal attribute, handling time attribute, and adopted performance measure. Carlo *et al.* (2015) focused on the seaside MCT operations and reviewed the relevant research efforts on berth allocation and quay crane scheduling. Furthermore, integrated seaside decision problems were discussed as well. Bierwirth and Meisel (2015) performed a follow-up survey to the previous survey by Bierwirth and Meisel (2010) and adopted the same classification of studies. More recently, Rodrigue and Agra (2022) conducted a literature survey on berth allocation and quay crane assignment and scheduling. However, their survey study mainly concentrated on the research efforts addressing uncertainty. No holistic and comprehensive BASP survey studies have been conducted after the study performed by Bierwirth and Meisel (2015). Therefore, the present study offers the following contributions to the scientific community and practitioners:

(i) A detailed and holistic state-of-the-art literature survey on BASP research is conducted. A total of 94 relevant studies not included in the former survey study by Bierwirth and Meisel (2015) were reviewed and critically analyzed focusing on discrete berth allocation and scheduling, continuous berth allocation and scheduling, and hybrid berth allocation and scheduling.
(ii) Representative mathematical formulations are presented for the DBASP, CBASP, and HBASP studies, serving as the guidance for the BASP research efforts that will be conducted in the future.
(iii) The reviewed studies are evaluated in a systematic way, focusing on the arrival and handling time assumptions, developed mathematical formulations, considered objective functions, employed solution approaches, and special considerations in the studies.
(iv) A strong emphasis is given to the solution methods that have been developed and deployed for different types of BASP mathematical models over the past years.
(v) The limitations identified in the contemporary and previous research efforts on berth allocation and scheduling are outlined. The future research needs summarized (based on the review of state-of-the-art studies) are illustrated.

The remaining sections of this study are developed as follows. The efforts devoted to the identification of relevant studies are presented in Section 2 along with the literature search methodology. A comprehensive and detailed description of the collected studies is provided in Section 3. Furthermore, supporting mathematical formulations and future research needs for each BASP study category are discussed in Section 3 as well. Section 4 discusses some of the critical research needs related to the development of BASP solution methods. The main conclusions of this survey study are presented in Section 5.

2. Literature Search

Conducting a comprehensive literature survey requires the implementation of a thorough literature search process. The content analysis approach was deployed in this study to perform a thorough literature search on berth allocation and scheduling as part of this research survey (Krippendorff, 2018). In order to conduct the literature search, this study accessed the major search engines (i.e., Web of Science, IEEE Explore, Springer Link, Google Scholar, and Scopus). A number of keywords and combinations of them were employed to guide the search process, such as berth allocation, berth scheduling, discrete berth allocation, continuous berth allocation, hybrid berth allocation, discrete berth scheduling, continuous berth scheduling, hybrid berth scheduling, berth allocation problem (BAP), berth scheduling problem, marine containers terminals, marine container terminal operations, etc. After the initial search, hundreds of relevant research efforts were discovered. The current study particularly focused on the research efforts that were authored in English and disseminated through peer-reviewed journals, conference proceedings, and doctoral dissertations. Studies that were written in other languages were not taken into account. Moreover, the studies dealing with other MCT operations (e.g., quay crane assignment, quay crane scheduling, internal transport, and yard operations) and integrated operations were not considered. The BASP studies covered in the former survey study by Bierwirth and Meisel (2015) were excluded from a detailed analysis as well.

After a thorough evaluation of the identified studies, a total of 94 studies on the BASP, which were not included in the last relevant comprehensive literature survey (Bierwirth & Meisel, 2015), were selected for a detailed evaluation. These studies were all strongly associated with the theme of the present literature analysis. Fig. 2 presents the distribution of identified BASP studies by year of publication. A total of 14 studies, which were published in 2015 and before but were not covered by the survey conducted by Bierwirth and Meisel (2015), were included in the present survey. It can be observed that the problem of berth allocation and scheduling is drawing more and more attention from the worldwide scientific community. Such a tendency can be explained by a

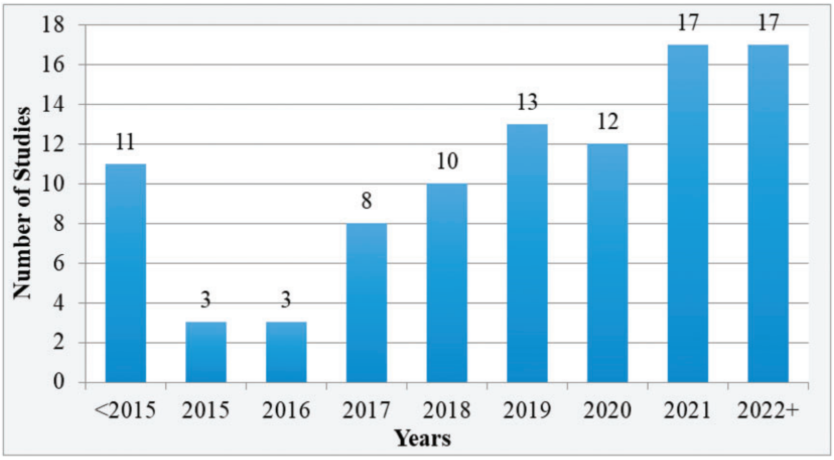

Figure 2: Distribution of BASP studies by year of publication.

Table 1: Distribution of selected BASP studies by journal.

Journal	Number of studies
Computers & Industrial Engineering	5
Transportation Research Part E: Logistics and Transportation Review	4
European Journal of Operational Research	3
Flexible Services and Manufacturing Journal	3
Maritime Business Review	3
Transportation Research Part B: Methodological	3
Applied Intelligence	2
Computers & Operations Research	2
Electronics	2
Engineering Optimization	2
IEEE Transactions on Intelligent Transportation Systems	2
Iranian Journal of Science and Technology, Transactions of Civil Engineering	2
Journal of the Operational Research Society	2
SN Computer Science	2
Transportation Research Record	2
Others	37

significant increase in seaborne trade and international transportation volumes. This literature survey primarily focused on scientific papers published in peer-reviewed journals (76 in total), conference proceedings (14 in total), and doctoral dissertations (4 in total). It was found that the BASP studies selected for a detailed review were mainly published in the leading international journals, including Computers & Industrial Engineering, Transportation Research Part E: Logistics and Transportation Review, European Journal of Operational Research, Flexible Services and Manufacturing Journal, Maritime Business Review, and Transportation Research Part B: Methodological (see Table 1).

The selected studies were classified into the following three categories for a further analysis: (i) studies on the DBASP – this group especially focuses on berth allocation and scheduling studies assuming a discrete berthing layout; (ii) studies on the CBASP – this group especially focuses on berth allocation and scheduling studies assuming a continuous berthing layout; and (iii) studies on the HBASP – this group especially focuses on berth allocation and scheduling studies assuming a hybrid berthing layout. Fig. 3 illustrates the distribution of identified BASP studies by subject category. It can be indicated that hybrid berth allocation and scheduling drew relatively less attention from researchers and practitioners, as only eight of the assessed studies (8.51% among all the selected studies) fell under this category. In contrast, BASPs with discrete or continuous layouts received greater attention, as 54 studies (57.45% among all the selected studies) and 32 studies (34.04% among all the selected studies) were identified for these two subject categories, respectively. Some studies could be associated with multiple research categories, and these studies were classified based on their primary emphasis.

3. Review of the Collected Studies

This section provides a thorough review and analysis of the state-of-the-art on berth allocation and scheduling literature collected through the literature search. Concise descriptions of the reviewed studies are organized and presented. The reviewed studies are analyzed and summarized under the aforementioned three categories (i.e., DBASP, CBASP, and HBASP) with concentration on: (i) arrival and handling time assumptions; (ii) types of the developed mathematical formulations; (iii) objective functions; (iv) adopted solution approaches; and (v) special considerations. Future research directions are outlined for each study category based on the identified limitations. Tables 2–4 provide the list of abbreviations that were adopted for the problem features, mathematical formulation types, and solution approaches. A detailed

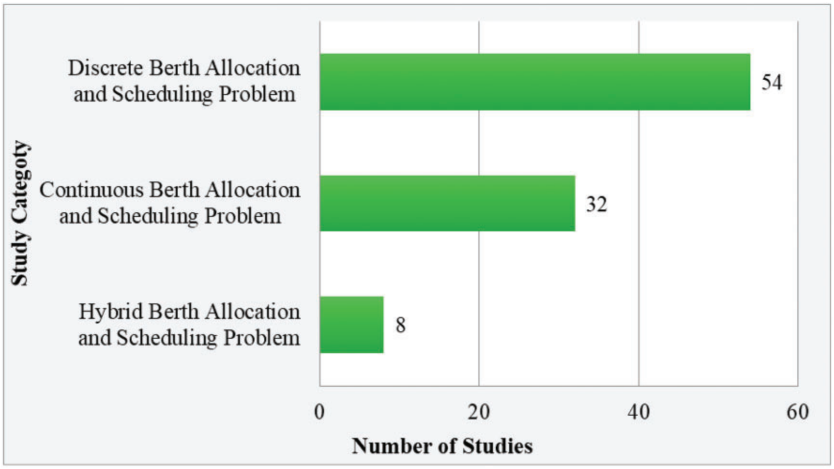

Figure 3: Distribution of BASP studies by study category.

Table 2: Abbreviations adopted for the problem features.

Description	Abbreviation
1. *Problem classification*	
Berth allocation problem	BAP
Berth scheduling problem	BSP
Multiple berth scheduling problem	MBSP
Multi-agent berth allocation problem	MABAP
Strategic berth template problem	SBTP
Berth allocation and scheduling problem	BASP
Discrete berth allocation and scheduling problem	DBASP
Continuous berth allocation and scheduling problem	CBASP
Hybrid berth allocation and scheduling problem	HBASP
Discrete dynamic berth allocation and scheduling problem	DDBASP
Discrete static berth allocation and scheduling problem	DSBASP
Continuous dynamic berth allocation and scheduling problem	CDBASP
Continuous static berth allocation and scheduling problem	CSBASP
Hybrid dynamic berth allocation and scheduling problem	HDBASP
Hybrid static berth allocation and scheduling problem	HSBASP
2. *Terminal classification*	
Dedicated container terminal	DCT
Marine container terminal	MCT
Multi-user container terminal	MUCT
3. *Spatial attributes*	
Discrete	D
Continuous	C
Hybrid	H
4. *Ship arrivals*	
Dynamic	D
Static	S
Uncertain	U
5. *Handling times*	
Variable	V
Fixed	F
Uncertain	U
6. *Performance measures*	
Deviation from a preferred berthing position	Dev
Departure earlier than scheduled	Early
Handling time of ships	Hand
Departure later than scheduled	Late
Actual berthing position	Pos
Waiting time of ships	Wait
Other performance measures (not listed above)	Other
Weighted coefficient	W

Table 4: Abbreviations adopted for the solution approaches.

Solution approach	Abbreviation
Adaptive large neighborhood search	ALNS
Adaptive grey wolf optimizer	AGWO
Alternate heuristic information	AHI
Ant colony system	ACS
Beam search	BS
Bee colony optimization	BCO
Branch-and-bound	B&B
Branch-and-price	B&P
Column enumeration	CE
Column generation	CG
Cuckoo search algorithm	CSA
Dynamic programming-based matheuristic	DP-Math
Evolutionary algorithm	EA
First come first served	FCFS
Genetic algorithm	GA
Grey wolf optimizer	GWO
Heuristic algorithm	HA
Hybrid queue priority	HQP
Machine learning	ML
Memetic algorithm	MA
Multiple queue model	MQM
Partial solution memory	PSM
Particle swarm optimization	PSO
Process for agent societies specification and implementation	PASSI
Sailfish-based algorithm	SFA
Simulated annealing	SA
Simulation-optimization	SO
Tabu search	TS
Truncated column generation	TCG
Universal island-based metaheuristic algorithm	UIMA
Variable neighborhood search	VNS

Table 3: Abbreviations adopted for the mathematical formulation types.

Mathematical formulation type	Abbreviation
Integer programming	IP
Linear programming	LP
Mixed integer linear programming	MIP/MILP
Mixed integer non-linear programming	MINLP
Mixed integer second order cone programming	MISOCP
Not applicable	N/A

description of the notations used in the representative mathematical models for the DBASP, CBASP, and HBASP decision problems (i.e., sets, decision variables, auxiliary variables, and parameters) is provided in Appendix 1.

3.1. Discrete berth allocation and scheduling

The collected DBASP studies are further reviewed and summarized in this section. A total of 54 studies were classified under the DBASP category. A representative optimization model for the discrete dynamic berth allocation and scheduling problem (**DDBASP**) can be presented as follows (Imai *et al.*, 2001).

The objective (1) of the **DDBASP** optimization model minimizes the total cost of berth allocation and scheduling in discrete berthing settings, including the overall handling cost of ships, the overall waiting cost of ships, and the overall cost of late ship departures. Constraints (2) ensure that every arriving ship is scheduled for service at one of the berthing segments in any service order. Constraints (3) indicate that no more than one ship can be serviced at a given berthing segment in a particular service order. Constraints (4) ensure that the ship length does not exceed the length of the assigned berthing segment. Constraints (5) indicate that the assigned berthing segment should have an adequate depth to service the given ship. Constraints (6) enforce the condition that the service of a given ship will start only after the arrival of that ship. Constraints (7) compute the start service time of every ship arriving at the considered MCT. Constraints (8) compute the waiting time of every ship arriving at the considered MCT. Constraints (9) compute the end service time of every ship arriving at the considered MCT. Constraints (10) compute the late departure time of every ship arriving at the considered MCT. Constraints (11) and (12) represent the integrality constraints of the parameters and variables of the **DDBASP** optimization model.

3.1.1. *Review of the collected DBASP studies*

Boile *et al.* (2006) converted the non-linear model developed by Imai *et al.* (2003) into a linear formulation with constrains to reduce the computational complexity. With the objective of minimizing the total weighted turnaround time of ships, the practices utilized by maritime industry operators to reach contractual service agreements were incorporated by considering the service priority. Zhou *et al.* (2006) minimized the total weighted waiting time of ships. Based on the ship waiting time, a variable service priority scheme was proposed without considering the "first come first served" (FCFS) rule to develop effective berth schedules. Gkolias (2007) developed multiple novel formulations to capture the BASP real-world operational attributes ignored by the former models. A remarkable share of the actual practices was investigated while adopting the least amount of assumptions. The presented heuristic algorithms (HAs) and formulations could be applied for the BASP decision problem and extended to other domains. Golias *et al.* (2010a) combined the environmental concerns into berth allocation and scheduling. Two critical components were incorporated into the optimization model: (i) minimization of the total ship turnaround time and late departures; and (ii) minimization of the consumed fuel and emission pollution. The developed evolutionary algorithm (EA)-based heuristic effectively derived berth schedules and showed some managerial insights.

Golias *et al.* (2010b) took a large number of the MCT operational objectives into account. A unified MIP formulation was proposed for the minimization of total ship turnaround cost, along with minimizing the penalty for tardiness and deviation from the optimal productivity. Premiums or negative cost components were incorporated as the compensation for completing service on time or before the requested time. Sun (2012) investigated multiple berth scheduling problem (MBSP) integrated with quay crane scheduling and developed a branch-and-price algorithm, an EA-based heuristic, and a tabu search (TS) to minimize the turnaround time of ships and penalties due to tardiness in departures. Cubillos *et al.* (2013) aimed to develop an analytical system and maximize the terminal productivity with a multi-agent berth allocation problem strategy. The proposed decision support system was built in the JADE environment, and the process for agent societies specification and implementation (PASSI) technique was utilized for modeling.

Dulebenets (2015) presented a novel contract agreement between operators of dedicated and multi-user terminals. The contract permitted ships to be diverted from a dedicated container terminal (DCT) to a multi-user container terminal (MUCT). A memetic algorithm (MA) was presented to address the non-linear

DDBASP: Discrete dynamic berth allocation and scheduling problem

$$min[\sum_{s\in S}\sum_{b\in B}\sum_{o\in O}(HT_{sb}\boldsymbol{x}_{sbo}c_s^{HT})+\sum_{s\in S}(\boldsymbol{WT}_s c_s^{WT})+\sum_{s\in S}(\boldsymbol{LD}_s c_s^{LD})] \tag{1}$$

Subject to:

$$\sum_{b\in B}\sum_{o\in O}\boldsymbol{x}_{sbo}=1\ \forall s\in S \tag{2}$$

$$\sum_{s\in S}\boldsymbol{x}_{sbo}\le 1\ \forall b\in B, o\in O \tag{3}$$

$$(L_b^{\text{berth}}-L_s^{\text{ship}})\boldsymbol{x}_{sbo}\ge 0\ \forall s\in S, b\in B, o\in O \tag{4}$$

$$(D_b^{\text{berth}}-D_s^{\text{ship}})\boldsymbol{x}_{sbo}\ge 0\ \forall s\in S, b\in B, o\in O \tag{5}$$

$$\sum_{\bar{s}\in S:\bar{s}\neq s}\ \sum_{\bar{o}\in O:\bar{o}<o}(HT_{\bar{s}b}\boldsymbol{x}_{\bar{s}b\bar{o}}+\boldsymbol{y}_{\bar{s}b\bar{o}})+\boldsymbol{y}_{sbo}-(AT_s-BA_b)\boldsymbol{x}_{sbo}\ge 0\ \forall s\in S, b\in B, o\in O \tag{6}$$

$$\boldsymbol{ST}_s\ge\sum_{\bar{s}\in S:\bar{s}\neq s}\ \sum_{\bar{o}\in O:\bar{o}<o}(HT_{\bar{s}b}\boldsymbol{x}_{\bar{s}b\bar{o}}+\boldsymbol{y}_{\bar{s}b\bar{o}})+\boldsymbol{y}_{sbo}+BA_b-M(1-\boldsymbol{x}_{sbo})\ \forall s\in S, b\in B, o\in O \tag{7}$$

$$\boldsymbol{WT}_s\ge\boldsymbol{ST}_s-AT_s\ \forall s\in S \tag{8}$$

$$\boldsymbol{ET}_s\ge\boldsymbol{ST}_s+\sum_{b\in B}\sum_{o\in O}(HT_{sb}\boldsymbol{x}_{sbo})\ \forall s\in S \tag{9}$$

$$\boldsymbol{LD}_s\ge\boldsymbol{ET}_s-RD_s\ \forall s\in S \tag{10}$$

$$\boldsymbol{x}_{sbo}\in\mathbb{B}\forall s\in S, b\in B, o\in O \tag{11}$$

$$\boldsymbol{y}_{sbo},\boldsymbol{ST}_s,\boldsymbol{ET}_s,\boldsymbol{WT}_s,\boldsymbol{LD}_s,BA_b,AT_s,HT_{sb},\ RD_s,\ L_s^{\text{ship}},L_b^{\text{berth}},D_s^{\text{ship}},D_b^{\text{berth}},c_s^{HT},c_s^{WT},c_s^{LD},M\in\mathbb{R}^+\forall s\in S, b\in B, o\in O \tag{12}$$

mixed integer formulation. The proposed model's objective was to generate ship schedules at both DCT and MUCT while reducing handling costs and late departure penalty and maximizing premiums due to early departures. Hu (2015) took into account a daytime preference in berth allocation and scheduling. A bi-objective formulation was proposed with the objective to minimize the workloads scheduled during the nighttime and the delay in operations. A multi-objective genetic algorithm based on the NSGA-II algorithm attributes was presented as a solution approach. Tsai *et al.* (2015) proposed a wharf-based EA for a BASP optimization model, aiming to minimize the total ship waiting time. The developed algorithm relied on certain problem-specific properties in order to speed-up convergence. The computational experiments demonstrated promising performance of the proposed algorithm. Paul and Chakraborty (2016) developed an EA-based algorithm for the DDBASP with the objective to minimize the waiting time. It was found that the proposed method improved the MCT productivity.

Dulebenets (2017a) proposed a DDBASP formulation with the objective of minimizing the total cost of ship service. An EA with a deterministic parameter control was designed as a solution method. A local search algorithm based on the FCFS rule was employed. With the implementation of a novel mutation operator, the mutation rates were altered based on a deterministic parameter control strategy. Later, Dulebenets (2017b) applied an adaptive parameter control strategy within an EA framework for the DDBASP decision problem minimizing the total cost of ship service. An adaptive mechanism was included in the presented mutation operator. The pollution due to carbon dioxide emission during the MCT operations was studied by Dulebenets *et al.* (2017). A hybrid EA metaheuristic was developed to minimize the cost generated in the waiting and handling stages, as well as the cost for tardiness in departures and the cost due to emission. The employment of local search heuristics remarkably enhanced the searching efficiency. A multi-criteria mathematical formulation was proposed by Issam *et al.* (2017) to minimize the total turnaround time and the amount of carbon dioxide emission during ship service. The physical constraints of berths and ships were considered. The model was solved with the CPLEX solver. A conventional BAP optimization model was enhanced by Dulebenets *et al.* (2018a) to take into account the possibility of diverting service requests to an external MCT at an additional cost from the initially planned multi-user MCT. Minimization of the total turnaround and late departure costs was the main objective function. A customized MA was developed for the problem, which was found to be computationally effective.

A self-adaptive EA was proposed by Dulebenets *et al.* (2018b) to solve a mixed integer linear programming (MILP) formulation for the minimization of total weighted waiting, handling time, and late departures. The proposed self-adaptive parameter control policy successfully improved the objective value within acceptable computational time. A comparison between the simulated annealing (SA) and EA algorithms with regard to their effectiveness for a DDBASP decision problem was conducted by Pereira *et al.* (2018). In terms of objective function values, different variants of the EA method with various crossover operators outperformed SA. The experiments demonstrated the necessity for a dynamic equilibrium between intensification and diversification. A DDBASP solution approach with two stages was developed by Barbosa *et al.* (2019). The operator combination with the best performance was identified using the free disposal hull models and data envelopment analysis. The objective function values were noticeably enhanced by the proposed EA and scatter search hybridization. Jos *et al.* (2019) concentrated on the minimization of ship service cost and penalty for tardiness. The benefit from early completion of service was taken into account as well. The authors designed and assessed three novel MILP formulations to address the investigated problem.

With the objective to optimize the allocation and schedule of berths and mitigate the congestion at an MCT, Kallel *et al.* (2019) constructed and examined an MILP model minimizing the total ship waiting and handling time. CPLEX was applied as the solution method for the case study of the Port of Rades, Tunisia. Kavoosi (2019) provided three alternative approaches (i.e., two EAs embedded with the self-adaptive parameter control strategies and a universal island-based metaheuristic) to solve diverse DDBSP mathematical formulations. The presented solution techniques could help MCT operators create berth schedules and act as potential decision support tools. Kavoosi *et al.* (2019a) developed a universal island-based metaheuristic algorithm (UIMA) for the enhancement of MCT productivity. Four distinct algorithms [i.e., differential evolution algorithm, estimation of distribution algorithm, particle swarm optimization (PSO), and EA] were simultaneously deployed by UIMA. With the utilization of different operators, the suggested UIMA approach yielded near-optimal solutions and outperformed some of the existing algorithms. A self-adaptive EA was also developed by Kavoosi *et al.* (2019b) to address an MILP model formulated for the DDBASP. An enhanced self-adaptive parameter control strategy was employed for the searching procedure. The proposed method generated high-quality berth schedules at convergence and outperformed nine popular metaheuristic algorithms.

From a mathematical standpoint, Kramer *et al.* (2019) offered two novel formulations for the DDBAP. The first formulation was time-indexed, and the second was an arc-flow model. A modeling upgrade and a variable-fixing strategy were created to eliminate some variables after considering the related costs to speed up the computational process. The utilization of suggested techniques improved the solution quality. Uncertain ship arrivals were analyzed by Schepler *et al.* (2019). A number of proactive, reactive, and proactive/reactive strategies were suggested by the study. The proactive/reactive technique based on stochastic dynamic programming (DP) and iterated TS was effective when uncertainties were limited. For the situations with greater degrees of uncertainty, the proposed pure reactive technique performed significantly better than the alternative strategies. Wang *et al.* (2019) suggested a metaheuristic method that incorporated a local search and the Levy flight random walk to solve the DDBASP model. The tidal time windows were considered along the search process aiming to achieve two major goals: (i) reduce the overall service cost of the incoming ships; and (ii) attain optimal allocation of arriving ships to berths considering tidal time constraints. Dulebenets (2020) offered a revolutionary adaptive island EA. Separate EAs were applied on each island simultaneously, and the adaptive process exchanged individuals among different islands. The search process was facilitated with the utilization of the periodic exchange of individuals among the islands. The suggested approach significantly improved the objective function value.

El Hammouti *et al.* (2020) investigated a standard BASP formulation for different layouts to maintain service satisfaction while decreasing the ship total turnaround time at MCTs. CPLEX and a sailfish-based algorithm (SFA) were implemented to solve the model. The numerical tests revealed that the hybrid layout was superior to the continuous and discrete layouts, and the utilization of a hybrid layout could minimize the service time and improve productivity. Nishi *et al.* (2020) minimized the total weighted turnaround time with a DP-based matheuristic. The upper and lower bounds were derived using the proposed approach. Congestion scenarios were captured and investigated. Sheikholeslami *et al.* (2020) analyzed the Shahid Rahaee shallow port of Iran. Ships with large drafts could not sail through the low-depth channel during the ebb time. Tidal windows were considered in the MILP model. It was indicated that the implementation of dredging could significantly decrease the tardiness in ship departures.

Based on the first-to-finish rule, Ankita and Mathirajan (2021) developed an HA to solve an MILP model for the DDBASP, aiming to minimize the total ship service time at an MCT. Based on the conducted numerical experiments, HA provided solutions that were close to the optimal ones derived using LINGO. Bacalhau *et al.* (2021) assessed two EA-inspired metaheuristics that relied on the application of approximated DP. A confinement procedure and an elimination process were used for solution space reduction. The computational experiments showed competitive performance of the algorithms, especially for large-scale instances. Barbosa *et al.* (2021) analyzed a method to fulfill time window constraints. With multiple statistical functions integrated, a dataset generator was proposed. An EA and a PSO were utilized to solve the DDBASP mathematical formulation that took time window constraints into account. It was determined that the method of penalization was capable of satisfying time window constraints. Cervellera *et al.* (2021) investigated a policy optimization for the DDBASP. The problem was described as evolving in which berths were assigned according to a parameterized policy function. A cross-entropy optimization method was used to adjust the parameters. The method was found to be universal for various scenarios and capable of adjusting to different real-world requirements.

Berth allocation and scheduling at an automotive container terminal was studied by Dkhil *et al.* (2021). Multiple mathematical formulations were provided, which took the vehicle flows into consideration. Practical real-world constraints were taken into account to assess the traffic flow and reduce the risk of vehicle collisions. The developed formulations were examined with the dataset collected from the Le Havre seaport, France. Korekane and Nishi (2021) developed a branch-and-bound (B&B) algorithm combined with a neural network for the DDBASP to define the node search priority. The superiority of the proposed method was demonstrated during the experiments with a large amount of berths and ships, where the standard B&B approach became less efficient for large search spaces. Liu *et al.* (2021a) proposed a tailored adaptive large neighborhood search (ALNS) algorithm for a sequencing problem of incoming ships in a one-way access channel. The integrated berth scheduling problem was formulated with an MILP model, and several real-world constraints were considered. The lower bound was defined with the utilization of a column generation (CG) method.

Channel constraints were also taken into account for a short-term BASP by Liu *et al.* (2021b). The movements of ships around the harbor and between multiple mooring positions were considered. A CG algorithm was applied to solve the formulated set partitioning model. The experiments were conducted with the dataset collected from the Port of Jingtang, China. The proposed method outperformed GUROBI, truncated CG, and column enumeration method. Mahpour *et al.* (2021) investigated the internal association between significant control parameters related to MCT operations, such as the allocation of equipment, spatial attributes of berths and ships, service efficiency, number of containers, and others. The total turnaround of ships was optimized with an EA-based method. It was implied that the depth of channel and sufficiency of berths were important for the minimization of waiting periods. Mnasri and Alrashidi (2021) developed a multi-agent framework to simulate the DDBASP and minimize the total ship turnaround time. A variety of techniques, such as the worst-fit arrangement approach, multi-agent interactions, and the contract net negotiation protocol, were incorporated. A series of numerical experiments were conducted, and the suggested multi-agent technique outperformed the alternative algorithms.

A cooperative method was presented by Peng *et al.* (2021) to schedule berth service and allocate shore power. Two objectives were optimized: (i) minimization of shore power system construction and utilization cost; and (ii) minimization of greenhouse gas emission. A PSO was deployed to solve the multiple-objective model. The proposed methodology can substantially improve sustainability of MCT operations. Prencipe and Marinelli (2021) studied the MCT operations at the Port of Livorno, Italy. The authors proposed a DDBASP mathematical formulation, and a bee colony optimization (BCO)-based metaheuristic was applied as the solution approach. The developed algorithm demonstrated competitive performance against CPLEX and Ant Colony Optimization

(ACO). Xiang and Liu (2021) examined a DDBASP with stochastic handling times at the tactical level. Historical data were processed and included in the robust optimization formulation. The objective was to minimize the penalty in berthing time deviation. A *K*-means clustering was utilized to develop the uncertainty set, and a column-and-constraint generation method was proposed to solve the resulting problem. The tendency of using dedicating berths in practice was considered by Zheng *et al.* (2021). The study mainly addressed a special DDBASP variant with liner carrier clustering. Stability and resilience were provided by the application of queuing theory and core theory. It was demonstrated that various liner carriers could benefit from cooperation, the operational cost could be reduced, and the berth utilization could be increased.

Al-Refaie and Abedalqader (2022) took unexpected events into account to plan for ship arrivals. The objective was to maximize the number of served emergent ships while minimizing disruptions to the scheduled ship service. Three consecutive models were proposed. It was found that the proposed methodology could be deployed to reach acceptable satisfaction levels for emergent and regular ships. Fernández and Munoz-Marquez (2022) analyzed the strategic berth template problem. Medium-term berth planning decisions were investigated. The availability of berths was captured as a constraint. A viable formulation was produced by disaggregating the beginning service time variables for the various berths. A cooperative system among liner shipping companies was proposed as an extension of the DDBASP by Guo *et al.* (2022). The liner carriers were clustered into groups, and the available berths were allocated appropriately for the clusters. CPLEX was incorporated within an EA to solve the developed mixed integer non-linear programming (MINLP) model. Hameed *et al.* (2022) integrated red colobus monkey optimization with an EA to solve the DDBASP at the Port of Paranaque and Antonina, Brazil. The proposed solution method demonstrated competitive performance against CPLEX and BCO.

Martin-Iradi *et al.* (2022) investigated collaboration between liner carriers and MCT operators in the multiport BASP. The optimization of sailing speed between different ports was included. The objective function aimed to minimize the fuel consumption when sailing between ports and the ship service cost at MCTs. A branch-and-cut-and-price algorithm was applied along with cooperative game theory methods to guarantee a win-win situation. Oudani and Benghalia (2022) considered stochasticity in ship arrival and handling times. The objective of the DBASP model was to minimize the total ship turnaround time with fuzzy constraints. Fuzzy models were converted into crisp ones with a parametric approach. Wang *et al.* (2022) analyzed the DDBASP as the combinatorial permutation problem. An adaptive heuristic information approach was incorporated into the ant colony system (ACS), which was developed to solve the problem. Divide-and-conquer and partial solution memory strategies were designed to enhance the computational efficiency. Yu *et al.* (2022) suggested a robust berth allocation strategy to reduce carbon emissions. The proposed model considered uncertainty in ship arrival and operational times. The robustness of schedules was studied to maintain emission variability within a small range while reducing carbon emissions. An EA-based algorithm was adopted as a solution approach. Yin *et al.* (2022) is the only study under this category that assumed static ship arrivals (i.e., DSBASP). The authors proposed an iterative variable grouping EA for the DSBASP considering tidal conditions. The numerical experiments indicated that the proposed approach could obtain effective berth schedules even for large-scale problems.

3.1.2. *Summary of the DBASP literature*

Table 5 presents a detailed summary of findings that were revealed after the review of collected DBASP studies. In particular, the table showcases a concise summary of berth spatial attributes, ship arrival classifications, handling time types, formulation types, objective components considered, adopted solution approaches, and special DBASP considerations. It can be observed that a significant number of DBASP studies considered dynamic ship arrivals and variable handling times (a total of 75.9% of studies). Approximately 13.0% of the DBASP studies modeled dynamic ship arrivals and fixed handling times. Furthermore, ship waiting and handling times were found to be the most popular components of the objective functions used in the proposed DBASP mathematical models. MIP and MINLP formulations were identified to be the most common types of formulations for the DBASP mathematical models. Heuristic and metaheuristic algorithms were found to be the most popular solution methods that were deployed to solve the DBASP decision problems. EA-based metaheuristics were the most frequently used among the collected DBASP studies. Distributions of the reviewed DBASP studies by ship arrival and handling times, objective components, mathematical formulations, and solution approaches are provided in Fig. 4.

3.1.3. *DBASP future research needs*

A number of research limitations were identified in the reviewed DBASP studies, which should receive more attention from the scientific community and practitioners in the following years. In particular, the following limitations were found to be the most common among the reviewed DBASP studies:

(i) Most of the models presented in the previously published DBASP studies focused on a few conventional objectives (e.g., minimize the total ship turnaround time, minimize the total delay in ship service completion, and minimize the total ship waiting time) and were mostly applied in single-objective settings (Dulebenets, 2017a, b; Hu, 2015; Wang *et al.*, 2022). Innovative formulations incorporating multiple conflicting objectives in an effective manner should receive more attention from the scientific community.

(ii) The total ship turnaround time at MCTs could be affected by various internal and external factors. Although several identified studies took the causes of uncertainties (e.g., impacts of weather, tidal windows, risk of congestion, handling productivity deviations, equipment breakdowns, etc.) into account to adapt for real-world scenarios, more advanced stochastic models should be developed in the following years to explicitly quantify the impacts of uncertainties on the DBASP decisions (Hu, 2015; Kavoosi *et al.*, 2019a, b; Liu *et al.*, 2021a, b; Schepler *et al.*, 2019; Wang *et al.*, 2022; Yu *et al.*, 2022). Stochastic parameters of the BASP models could be modeled by different methods (e.g., consideration of upper and lower bounds, Monte Carlo simulation, game-theoretic methods, and cardinality-constrained method).

(iii) The proposed DBASP optimization models and solution methods need to be thoroughly assessed with realistic operational data. More realistic datasets collected based on the daily MCT operations should be applied throughout the development and evaluation of optimization models formulated in relevant studies (Dulebenets, 2017a).

Table 5. Summary of findings: DBASP.

References	Spatial attribute	Ship arrivals	Handling times	Formulation types	Objective(s)	Solution approach	Special considerations
Boile *et al.* (2006)	D	D	V	MIP	Σ[w(Wait+Hand)]	GAMS	Took service priority into account
Zhou *et al.* (2006)	D	D	V	MINLP	Σ[w(Wait)]	EA	Ignored the FCFS strategy
Gkolias (2007)	D	D	V	MIP	Σ[w_1(Late)+w_2(Early)+ w_3(Wait)+w_4(Hand)]; Σ[w(Wait+Hand)]	EA; HA	Solution methods applicable to other problems
Golias *et al.* (2010a)	D	D	V	MINLP	Σ[w_1(Wait+Hand+Late) +w_2(Other)]	EA	Fuel consumption and emissions were minimized between consecutive ports
Golias *et al.* (2010b)	D	D	V	MIP	Σ[w_1(Wait)+w_2(Hand)+ w_3(Late)+w_4(Early)+ w_5(Other)]	CPLEX	Investigated various operational objectives
Sun (2012)	D&C	D	V	MIP	Σ[Wait+Hand+w(Late)]	EA; TS	Studied MBSP integrated with quay crane scheduling
Cubillos *et al.* (2013)	D	D	V	N/A	Σ[w_1(Other)+w_2(Other)]	HA	Proposed an agent-oriented decision system
Dulebenets (2015)	D	D	V	MINLP	Σ[w_1(Hand)+ w_2(Late)+w_3(Early)]	MA	A novel contractual arrangement between operators of dedicated and multi-user terminals
Hu (2015)	D	D	V	MIP	Σ(Late); Σ(Other)	EA	The preference for the daytime scheme was incorporated
Tsai *et al.* (2015)	D	D	V	MINLP	Σ(Wait)	EA	A novel wharf-based EA was presented
Paul and Chakraborty (2016)	D	D	V	MIP	Σ(Wait)	EA	A novel EA-based method was proposed
Dulebenets (2017a)	D	D	V	MINLP	Σ[w_1(Hand)+w_2(Wait)+ w_3(Late)+w_4(Early)]	EA with a deterministic parameter control	Deterministic parameter control strategy was embedded in an EA
Dulebenets (2017b)	D	D	V	MIP	Σ[w_1(Hand)+w_2(Wait)+ w_3(Late)]	Adaptive EA	The mutation rate was adjusted with an adaptive mechanism
Dulebenets *et al.* (2017)	D	D	V	MIP	Σ[w_1(Hand)+w_2(Wait)+ w_3(Late)+w_4(Other)]	Hybrid EAs	The cost of carbon dioxide emissions was minimized
Issam *et al.* (2017)	D	D	V	MIP	Σ[(Other)+Wait+Hand]	CPLEX	Emissions due to ship service were minimized
Dulebenets *et al.* (2018a)	D	D	V	MINLP	Σ[w_1(Hand)+w_2(Other) +w_3(Late)]	Hybrid EA	Service at an external MCT for diverted ships
Dulebenets *et al.* (2018b)	D	D	V	MIP	Σ[w_1(Hand)+w_2(Hand) +w_3(Late)]	Self-adaptive EA	The crossover and mutation probabilities were incorporated in the chromosomal encoding
Pereira *et al.* (2018)	D	D	V	MINLP	Σ[w(Wait+Hand)]	EA; SA	Compared SA and EA applications
Barbosa *et al.* (2019)	D	D	V	MIP	Σw(Wait+Hand)	Hybrid EA	Utilized free disposal hull formulations and data envelopment analysis
Jos *et al.* (2019)	D	D	V	MIP	Σ[w_1(Wait)+w_2(Hand) +w_3(Early)+w_4(Late)]	CPLEX	Three novel formulations presented
Kallel *et al.* (2019)	D	D	F	MIP	Σ(Wait+Hand)	CPLEX	Spatial constraints of berths and ships included
Kavoosi (2019)	D	D	V	MIP	Σ[w_1(Wait)+w_2(Hand)+ w_3(Late)]	Self-adaptive EA; augmented self-adaptive EA; universal island-based metaheuristic	Presented three promising solution methods

Table 5. Continued

References	Spatial attribute	Ship arrivals	Handling times	Formulation types	Objective(s)	Solution approach	Special considerations
Kavoosi *et al.* (2019a)	D	D	V	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Hand})+w_3(\text{Late})]$	Universal island-based metaheuristic	Proposed a universal island-based metaheuristic solution method for the DDBASP
Kavoosi *et al.* (2019b)	D	D	V	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Hand})+w_3(\text{Late})]$	Augmented self-adaptive EA	An augmented self-adaptive parameter control strategy
Kramer *et al.* (2019)	D	D	V	MIP	$\Sigma[w(\text{Wait+Hand})]$	CPLEX	An arc-flow model and a time-indexed model were developed
Schepler *et al.* (2019)	D	U	V	MIP	$\Sigma(\text{Wait+Hand})$	TS + DP	Proactive/reactive, reactive, and proactive strategies were proposed
Wang *et al.* (2019)	D	D	F	MIP	$\Sigma w(\text{Wait+Hand})$	Levy flight-based metaheuristic	Local search and Levy flight random walk were used
Dulebenets (2020)	D	D	V	MIP	$\Sigma[w_1(\text{Hand})+w_2(\text{Wait})+w_3(\text{Late})]$	Adaptive island EA	The developed approach operated multiple EAs concurrently on its islands and adaptively exchanged solutions between them
El Hammouti *et al.* (2020)	D&C&H	D	V	MIP	$\Sigma(\text{Wait+Hand})$	SFA	Three proposed formulations were compared using CPLEX and a SFA
Nishi *et al.* (2020)	D	D	V	MIP	$\Sigma[w(\text{Wait+Hand})]$	HA	Lower and upper bounds were found with a DP heuristic
Sheikholeslami *et al.* (2020)	D	D	F	MIP	$\Sigma(\text{Late})$	CPLEX	Constraints of a low-depth access channel were considered
Ankita and Mathirajan (2021)	D	D	V	MIP	$\Sigma(\text{Wait+Hand})$	HA	Provided a detailed derivation of ship handling time
Bacalhau *et al.* (2021)	D	D	V	MINLP	$\Sigma(\text{Wait+Hand})$	EA + DP	Two metaheuristics were developed based on a combination of EA and DP
Barbosa *et al.* (2021)	D	D	V	MIP	$\Sigma[w(\text{Wait+Hand})]$	EA; PSO	Coped with time window constraints
Cervellera *et al.* (2021)	D	D	V	N/A	$\Sigma w(\text{Wait+Hand})$	Cross-entropy optimization	A parameterized policy function was deployed for berth allocation
Dkhil *et al.* (2021)	D	D	V	MIP	$\Sigma(\text{Wait+Hand})$	CPLEX	An automotive transshipment terminal was studied
Korekane and Nishi (2021)	D	D	V	IP	$\Sigma w(\text{Wait+Hand})$	B&B	A neural network-based B&B method was proposed
Liu *et al.* (2021a)	D	D	F	MIP	$\Sigma w(\text{Wait+Hand})$	Tailored ALNS	The CG approach was used to define a lower bound
Liu *et al.* (2021b)	D	D	V	MIP	$\Sigma[w_1(\text{Wait+Hand})+w_2(\text{Other})]$	CG	Proposed a CG algorithm to solve an equivalent set-partitioning formulation
Mahpour *et al.* (2021)	D	D	V	N/A	$\Sigma(\text{Wait+Hand})$	EA	Ship loading and discharging operations were directly considered

Table 5. Continued

References	Spatial attribute	Ship arrivals	Handling times	Formulation types	Objective(s)	Solution approach	Special considerations
Mnasri and Alrashidi (2021)	D	D	V	MIP	Σ(Wait+Hand)	HA	A multi-agent approach was developed
Peng *et al.* (2021)	D	D	V	MINLP	Σw_1(Other); Σw_2(Other)	PSO	Minimized pollution emissions and reduced the cost of installing and operating shore power infrastructure
Prencipe and Marinelli (2021)	D	D	V	MIP	Σ(Wait+Hand)	BCO algorithm	A BCO-based algorithm was proposed
Xiang and Liu (2021)	D	D	U	MIP	$\Sigma[w_1$(Wait)+w_2(Early)]	Column-and-constraint generation algorithm	Stochastic factors were analyzed and taken into account
Zheng *et al.* (2021)	D	D	F	MIP	Σ[w(Other)]	Three-stage optimization	Proposed a three-stage model and clustered ships from various liner shipping carriers
Al-Refaie and Abedalqader (2022)	D	D	V	MINLP	Σ(Other)	LINGO	Maximized the number of emergent ships handled while incurring the least disturbance to the scheduled service
Fernández and Munoz-Marquez (2022)	D	D	F	MIP	Σ[w(Hand)+Wait]	HA	Combined operational and strategic schemes for the medium-term schedule
Guo *et al.* (2022)	D	U	U	MINLP	$\Sigma[w_1$(Wait+Hand)+ w_2(Other)]	EA; CPLEX	Liner clustering problem was integrated with berth scheduling
Hameed *et al.* (2022)	D	D	V	MINLP	Σ[Wait+Hand]	Red colobus monkey optimization + EA	A solution removal process and a low-reservation solution technique for less promising areas
Martin-Iradi *et al.* (2022)	D	D	V	MIP	$\Sigma[w_1$(Wait)+w_2(Hand)+ w_3(Late)+w_4(Other)]	Branch-and-cut-and-price algorithm	A BASP with multiple ports
Oudani and Benghalia (2022)	D	U	U	MIP	Σ(Wait+Hand)	N/A	Fuzzy models transformed to crisp ones with a parametric strategy
Wang *et al.* (2022)	D	D	F	MINLP	Σ(Wait)	Adaptive ACS algorithm	Divide-and-conquer and partial solution memory strategies were proposed
Yin *et al.* (2022)	D	S	F	MINLP	Σ[Hand+(Other_1)+(Other_2)]	Iterative variable grouping EA	Consideration of tidal constraints in berth scheduling
Yu *et al.* (2022)	D	U	U	MINLP	Σ(Other_1); Σ(Other_2)	EA	Generated robust schedules with low-carbon consideration

Note. Exact optimization approaches: B&B, branch-and-cut-and-price algorithm, CG, CPLEX, GAMS, and LINGO. Heuristic approaches: HA. Metaheuristic approaches: adaptive ACS algorithm, ALNS, BCO, EA, MA, PSO, red colobus monkey optimization, SA, SFA, and TS.

(iv) MCT operational efficiency is highly related to working productivity of on-site workers. There is a lack of quantified measurements for daytime operation preferences, operation safety, energy consumption efficiency and other human-related factors, which should be further addressed in the future studies (Hu, 2015).

(v) The real-world spatial constraints of MCT operations (e.g., ship draft requirements, berth dimensions, and navigation channel layout and dimensions) could directly affect berth allocation and scheduling and eventually influence service activities, which should be taken into consideration and evaluated more consistently in the future studies (Dulebenets, 2017a, b; Liu *et al.*, 2021a).

(vi) Only a few studies specifically modeled environmental considerations related to BASPs (e.g., the amount of emissions produced by the dedicated handling equipment throughout the service of arriving ships) (Dulebenets *et al.*, 2017; Issam *et al.*, 2017; Yu *et al.*, 2022). The future research should concentrate on a more detailed modeling of pollutants during the berthing period of ships to explicitly capture environmental issues associated with berth allocation and scheduling.

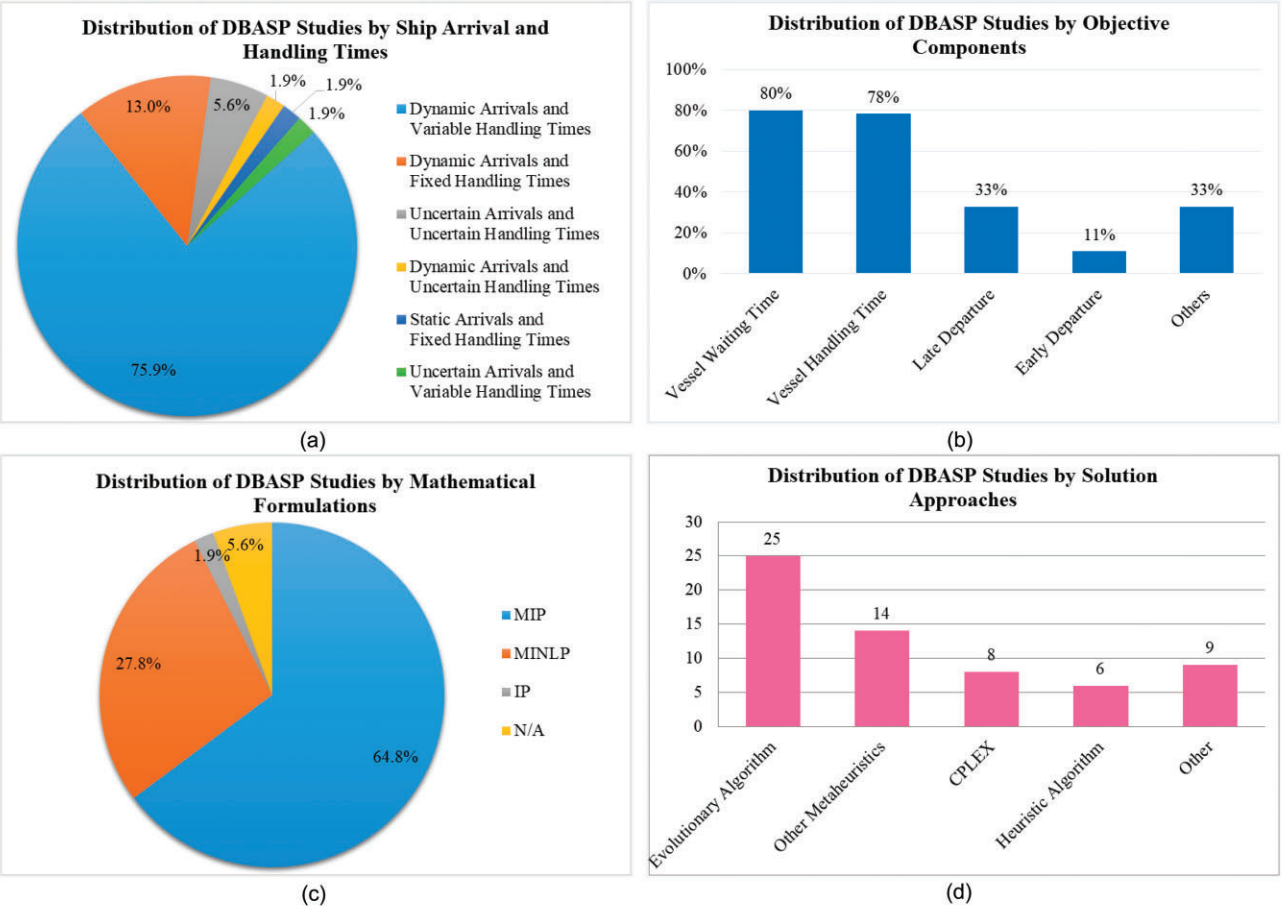

Figure 4: Distribution of the reviewed DBASP studies by (a) ship arrival and handling times, (b) objective components, (c) mathematical formulations, and (d) solution approaches.

(vii) Contractual agreements that exist between MCT operators and shipping lines should be more explicitly captured by the future DBASP studies (e.g., a dedicated MCT serving ships from a specific shipping line or a multi-user MCT serving ships from several shipping lines). Only a limited number of the collected DBASP studies captured this practical consideration (Dulebenets *et al.*, 2018a; Guo *et al.*, 2022; Zheng *et al.*, 2021), and more efforts should be devoted in the following years.

3.2. Continuous berth allocation and scheduling

The collected CBASP studies are further reviewed and summarized in this section. A total of 32 studies were classified under the CBASP category. A representative optimization model for the continuous dynamic berth allocation and scheduling problem (**CDBASP**) can be presented as follows (Imai *et al.*, 2005; Kim & Moon, 2003).

The objective (13) of the **CDBASP** optimization model minimizes the total cost of berth allocation and scheduling in continuous berthing settings, including the overall handling cost of ships, the overall waiting cost of ships, and the overall cost of late ship departures. Constraints (14) and (15) ensure that every ship to be serviced at the MCT is anchored within the boundaries of the wharf. Constraints (16) indicate that the assigned berthing position of the wharf should have an adequate depth to service the given ship. Constraints (17) thorough (19) prevent the ship service overlaps in time and space dimensions. Constraints (20) enforce the condition that the service of a given ship will start only after the arrival of that ship. Constraints (21) compute the waiting time of every ship arriving at the considered MCT. Constraints (22) compute the handling time of every ship arriving at the considered MCT, considering potential deviations from the preferred berthing position. Constraints (23) compute the end service time of every ship arriving at the considered MCT. Constraints (24) compute the late departure time of every ship arriving at the considered MCT. Constraints (25) and (26) represent the integrality constraints of the parameters and variables of the **CDBASP** optimization model.

3.2.1. *Review of the collected CBASP studies*

Javanshir and Seyed-Alizadeh Ganji (2010) presented an MILP formulation for the CDBASP, aiming to minimize the total ship service time. The proposed formulation was compared to the one developed by Imai *et al.* (2005). It was found that the proposed MILP model was superior to the previously published one and could be solved faster. Wang *et al.* (2013) developed a solution method for the CDBASP with an objective to address the limitations of the solution method proposed by Du *et al.* (2011). Two quadratic outer approximation techniques were developed to capture ship fuel consumption and were found to be superior to the solution method of Du *et al.* (2011) in terms of computational time. Legato *et al.* (2014) presented a simulation-optimization (SO) approach for tactical-level and operational-level CDBASP decisions. A mathematical model was deployed at the tactical level, and a simulation

CDBASP: Continuous dynamic berth allocation and scheduling problem

$$min[\sum_{s\in S}(\boldsymbol{HT}_s c_s^{HT}) + \sum_{s\in S}(\boldsymbol{WT}_s c_s^{WT}) + \sum_{s\in S}(\boldsymbol{LD}_s c_s^{LD})] \tag{13}$$

Subject to:

$$\boldsymbol{x}_s^{pos} + (L_s^{ship}/2) \le L^{wharf}\ \forall s \in S \tag{14}$$

$$\boldsymbol{x}_s^{pos} - (L_s^{ship}/2) \ge 0\ \forall s \in S \tag{15}$$

$$(D_s^{wharf} - D_s^{ship})\boldsymbol{x}_s^{pos} \ge 0\ \forall s \in S \tag{16}$$

$$\boldsymbol{x}_{\underline{s}}^{pos} + (L_{\underline{s}}^{ship}/2) \le \boldsymbol{x}_{\bar{s}}^{pos} - (L_{\bar{s}}^{ship}/2) - M(1 - \mathbf{z}_{\underline{s}\bar{s}}^{space})\forall \underline{s}, \bar{s} \in S, \underline{s} \ne \bar{s} \tag{17}$$

$$\boldsymbol{ST}_{\underline{s}} + \boldsymbol{HT}_{\underline{s}} \le \boldsymbol{ST}_{\bar{s}} - M(1 - \mathbf{z}_{\underline{s}\bar{s}}^{time})\forall \underline{s}, \bar{s} \in S, \underline{s} \ne \bar{s} \tag{18}$$

$$\mathbf{z}_{\underline{s}\bar{s}}^{space} + \mathbf{z}_{\underline{s}\bar{s}}^{time} = 1\forall \underline{s}, \bar{s} \in S, \underline{s} \ne \bar{s} \tag{19}$$

$$\boldsymbol{ST}_s \ge AT_s\ \forall s \in S \tag{20}$$

$$\boldsymbol{WT}_s \ge \boldsymbol{ST}_s - AT_s\ \forall s \in S \tag{21}$$

$$\boldsymbol{HT}_s = HT_s^{pref} + \alpha_s|\boldsymbol{x}_s^{pos} - x_s^{pref}|\ \forall s \in S \tag{22}$$

$$\boldsymbol{ET}_s \ge \boldsymbol{ST}_s + \boldsymbol{HT}_s\ \forall s \in S \tag{23}$$

$$\boldsymbol{LD}_s \ge \boldsymbol{ET}_s - RD_s\ \forall s \in S \tag{24}$$

$$\mathbf{z}_{\underline{s}\bar{s}}^{space}, \mathbf{z}_{\underline{s}\bar{s}}^{time} \in \mathbb{B}\forall \underline{s}, \bar{s} \in S, \underline{s} \ne \bar{s} \tag{25}$$

$$\boldsymbol{x}_s^{pos}, \boldsymbol{ST}_s, \boldsymbol{ET}_s, \boldsymbol{WT}_s, \boldsymbol{LD}_s, \boldsymbol{HT}_s, AT_s,\ HT_s^{pref}, RD_s,\ L_s^{ship}, L^{wharf}, D_s^{ship}, D_s^{wharf}, x_s^{pref}, \alpha_s, c_s^{HT}, c_s^{WT}, c_s^{LD},\ M \in \mathbb{R}^+\ \forall s \in S \tag{26}$$

model was developed for the operational level. A simultaneous consideration of tactical and operational decisions could better assist MCT operators with berth allocation and scheduling.

Sheikholeslami *et al.* (2014) took the tidal constraints into consideration when modeling berth allocation and scheduling decisions. An EA incorporated with a pattern search algorithm was developed to solve the proposed CDBASP formulation. Emde and Boysen (2016) minimized the total weighted waiting time and number of containers missed by intended ships. The ships calling for service at the MCT were explicitly classified as feeder ships and container ships. An SA-based algorithm was proposed as a solution approach and was found to be effective. Ismail *et al.* (2016) presented a tri-objective optimization model for continuous berth allocation and scheduling focusing on the following objective functions: (i) minimization of waiting time; (ii) minimization of makespan; and (iii) minimization of mean flow time. Dadashi *et al.* (2017) formulated an MIP formulation for the CDBASP with several MCTs and took into account the varied water depth in the access channel. To comply with the contractual arrangements between liner shipping companies and MCT operators, ships were categorized into priority groups. CPLEX was used to solve the optimization model. The computational experiments showed that the tidal impacts and service priorities could lead to significant schedule variations.

Xiang *et al.* (2017) presented a bi-objective robust formulation for the CBAP with a special focus on the economic performance and customer satisfaction. The objective aimed to minimize the total ship waiting cost, late departure cost, and the cost associated with deviations from the optimal berthing location. An adaptive grey wolf optimizer (AGWO) algorithm was developed to efficiently solve the model. The experiments confirmed competitive performance of the developed algorithm. Two SA algorithms were presented by Lin *et al.* (2018) to solve a mathematical model formulated for the CDBASP. Minimization of the total cost due to the deviation of ships from the scheduled berthing positions and the total ship turnaround time cost was the main objective function. The two proposed SA methods demonstrated their effectiveness against GUROBI and some of the state-of-the-art solution methods. Mohammadi and Forghani (2018) took into consideration uncertainties in ship arrival and handling times when modeling the CBASP operations. Minimizing the total expenses associated with waiting time, deviations from preferred berthing positions, and anticipated delay in ship departures was the objective of the presented optimization model. A hybrid SA-based algorithm was presented to solve the model. The numerical experiments highlighted the effects of stochastic parameters on the CBASP decisions.

Sheikholeslami and Ilati (2018) simulated the impact of tides on port operations and captured ship arrival time uncertainty. The objective of the presented optimization model minimized the total cost due earliness and tardiness in ship departures and deviation from the scheduled berthing positions. Ship arrival uncertainty was addressed by means of sample average approximation. Xu and Lee (2018) proposed a new relaxation method for the CDBAP and derived a new lower bound. The objective aimed to minimize the total weighted ship turnaround time. It was indicated that the proposed lower bound could be computed in quadratic time. Yuan (2018) adopted a cost-based approach for berth allocation and scheduling. The objective of the developed MIP model minimized the costs associated with the deviation of ships from their preferred berthing positions and late departures. AMPL was used to solve the presented mathematical formulation. Hsu and Chiang (2019) evaluated different solution methods for the CDBASP, including the FCFS policy, shuffled frog-leaping algorithm, and improved shuffled frog-leaping algorithm. The conducted experiments showcased the superiority of improved shuffled frog-leaping algorithm. Yan *et al.* (2019) suggested a berth-flow modeling methodology for the CBASP considering stochasticity in ship arrival times. The problem was formulated as an integer multi-commodity network flow model, and CPLEX was deployed to solve the resulting model.

Hu (2020) captured the emissions produced by ships throughout the mooring and sailing stages in the proposed CDBASP optimization model. The non-linear relationship between ship velocity and emissions was transferred to the linear one with the deployment of second-order cone programming. The formulation was solved with the epsilon-constraint approach. The computational experiments showed that the proposed methodology can be used to develop efficient berth schedules without sacrificing environmental sustainability. Li *et al.* (2020) provided a mathematical model for minimizing the total ship turnaround time at MCTs with a continuous berthing layout. A genetic-harmony search algorithm was developed to solve the proposed optimization model. It was found that the developed algorithm was able to find good-quality solutions within acceptable computational time. Liu *et al.* (2020) considered stochastic ship arrival and handling times in continuous berth allocation and scheduling. A two-stage methodology was presented, where the baseline schedule was developed before the occurrence of disruptions, and the recovery operations were planned afterwards. A set of numerical experiments indicated that the proposed method could yield robust berth schedules without substantially increasing the baseline cost.

A double-line ship mooring (DLSM) formulation was presented by Luo *et al.* (2020) to minimize the cost associated with deviations from desired berthing positions and late departures. Two ships could berth at one berthing position in the DLSM model when the inner ship is longer than the outside one. The proposed PSO solution method produced high-quality solutions. The DLSM model showcased superiority when compared to a single-line ship mooring model. Wu and Miao (2020) adopted a robust scheduling strategy to develop berth schedules, where ship arrival and handling times were not known with certainty. A simulation-based EA was deployed to generate a proactive scheme. The model attained a balance between effectiveness and robustness and was properly insensitive to the degree of uncertainty. Yıldırım *et al.* (2020) investigated the influence of ship service priorities. A hybrid queue priority rule was proposed and applied in the computational experiments along with the FCFS rule. The single queue model scenarios were proved to be superior to the multiple queue model scenarios with respect to the MCT throughput and berth utilization. Al-Refaie and Abedalqader (2021) developed two models for berth allocation and scheduling under regular and emergency situations. Maximization of the customer satisfaction level and minimization of the total ship turnaround time were the common objectives of the two models. LINGO was used to solve the developed optimization models. It was found that the proposed methodology could assist with berth planning under regular and emergency conditions.

Unpredictable weather conditions were integrated in the modeling of ship service by Guo *et al.* (2021). Weather uncertainties were considered and evaluated in the mathematical formulation. A machine learning (ML) approach was used to determine the relationship between weather conditions and ship handling time. It was concluded that assigning additional handling equipment could reduce ship handling times under different weather conditions. A scenario-based stochastic programming formulation with two stages was proposed by Park *et al.* (2021) to address uncertain ship arrivals. Time buffers were incorporated in the model as decision variables. A PSO algorithm with intelligent buffer time insertion was developed for the problem. Wu and Miao (2021) aimed to improve berth schedule robustness by incorporating baseline schemes with buffers. A system was proposed that could be potentially adapted to various BASP models. The minimization of late departures was the objective. The computational experiments indicated that the proposed approach could enhance operations flexibility and capture the impact of service priority. Agra and Rodrigues (2022) considered potential stochasticity in ship handling times when modeling the CBASP. A two-stage robust optimization model was proposed to minimize the total late ship departures. Probability distributions with various scenarios were applied to model uncertainties in ship handling times. The problem was solved with an exact decomposition algorithm.

Aslam *et al.* (2022a) examined berth allocation and scheduling at a multi-quay MCT with practical constraints (e.g., safety distances between ships). A cuckoo search algorithm (CSA) was proposed to minimize the total ship service cost associated with waiting and handling processes, mooring deviation, and late departures. The numerical experiments demonstrated the efficiency of proposed solution approach. Aslam *et al.* (2022b) also proposed an MILP model for the CDBASP to minimize the total turnaround cost. The proposed optimization model was solved using CSA, EA, and CPLEX. The experiments indicated that CSA was able to provide good-quality solutions within reasonable computational time. Kolley *et al.* (2022) proposed four different ML models in order to predict the values of ship arrival time and more accurately address the CBASP decisions. The robustness of the proposed model was enhanced by means of introducing dynamic time buffers. It was found that the developed ML models were able to accurately predict ship arrival times. Furthermore, the proposed methodology could also reduce ship waiting time and, hence, improve service quality of the arriving ships.

Pérez-Cañedo *et al.* (2022) proposed a CBASP optimization model, which directly captured uncertainties in ship arrival and handling times. The objective minimized the total ship waiting time and the makespan of ship handling operations. Two lexicographic methods were deployed to solve the problem. A fuzzy epsilon-constraint method was used to obtain multiple Pareto-optimal fuzzy solutions. Samrout *et al.* (2022) investigated transshipment movements in continuous berth allocation and scheduling. The objective of the presented optimization model minimized the total ship turnaround time and late departure penalty. The resulting decision problem was solved with an EA-based solution algorithm. The proposed algorithm was compared to CPLEX and was found to be effective. Tang *et al.* (2022) explored the CBASP from a proactive standpoint taking into account various interruptions that could cause uncertainties in ship arrival and handling times. A proactive optimization technique was designed for developing baseline schemes with the objective to minimize baseline costs in deterministic situations and recovery costs in case of disruptive events. A multi-stage EA-based solution procedure was proposed to produce robust schedules.

3.2.2. *Summary of the CBASP literature*

Table 6 presents a detailed summary of findings that were revealed after the review of collected CBASP studies. In particular, the table showcases a concise summary of berth spatial attributes, ship arrival classifications, handling time types, formulation types, objective components considered, adopted solution approaches, and special CBASP considerations. It can be observed that a significant number of CBASP studies considered dynamic ship arrivals and fixed handling times (a total of 46.9% of studies). Approximately 21.9% of the CBASP studies modeled uncertain ship arrivals and uncertain handling times. Furthermore, ship waiting and late departure times were found to be the most popular components of the objective functions used in the proposed CBASP mathematical models. MIP formulations were identified to be the most common types of formulations for the CBASP mathematical models. Metaheuristic algorithms were found to be the most popular solution methods that were deployed to solve the CBASP decision problems. However, a significant number of studies relied on CPLEX and other exact optimization approaches (a total of 31.3% of studies). Distributions of the reviewed CBASP

Table 6: Summary of findings: CBASP.

References	Spatial attribute	Ship arrivals	Handling times	Formulation types	Objective(s)	Solution approach	Special considerations
Javanshir and Seyed-Alizadeh Ganji (2010)	C	D	V	MIP	Σ(Wait+Hand)	LINGO	The proposed formulation was found to be more efficient than the one by Imai *et al.* (2005)
Wang *et al.* (2013)	C	D	F	MISOCP	$\Sigma[w_1(\text{Late})+w_2(\text{Other})]$	CPLEX	Two quadratic outer approximation techniques were developed to capture ship fuel consumption
Legato *et al.* (2014)	C	D	F	MIP	$\Sigma[w_1(\text{Dev})+w_2(\text{Wait})]$	SO	Both operational and tactical decisions were considered
Sheikholeslami *et al.* (2014)	C	D	F	MIP	Σ[w(Wait+Hand)+(Other)]	EA+ pattern search algorithm	Incorporated tidal time windows in the model
Emde and Boysen (2016)	C	D	F	MIP	Σ[w(Wait)+Other]	SA	Examined the interactions between feeder ships and container ships
Ismail *et al.* (2016)	C	D	F	MIP	Σ(Wait); Σ(Wait+Hand); Σ(Other)	Exact optimization	Proposed a multi-objective optimization model
Dadashi *et al.* (2017)	C	D	F	MIP	Σ[w(Late)]	CPLEX	The spatial constraints of access channel were assessed
Xiang *et al.* (2017)	C	U	U	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Late})+w_3(\text{Dev})]$	AGWO	An AGWO was proposed with service satisfaction and productivity considerations
Lin *et al.* (2018)	C	D	F	MIP	$\Sigma[w_1(\text{Wait+Hand})+w_2(\text{Dev})]$	SA	Ship allocation on both sides of the quay was investigated
Mohammadi and Forghani (2018)	C	U	U	MIP	$\Sigma[w_1(\text{Dev})+w_2(\text{Wait})+w_3(\text{Late})]$	SA	Captured stochasticity in ship arrival and handling times
Sheikholeslami and Ilati (2018)	C	U	F	MIP	$\Sigma[w_1(\text{Early})+w_2(\text{Late})+w_3(\text{Dev})]$	Sample average approximation	Simulated the impact of tides on port operations and captured ship arrival time uncertainty
Xu and Lee (2018)	C	D	F	MIP	Σw(Wait+Hand)	HA	A new lower bound was derived for the problem
Yuan (2018)	C	D	F	MIP	$\Sigma[w_1(\text{Dev})+w_2(\text{Late})]$	AMPL	Focused on berth allocation with a cost-based objective
Hsu and Chiang (2019)	C	D	V	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Hand})]$	Improved shuffled frog-leaping algorithm	Deployed three different solution approaches for the CDBASP
Yan *et al.* (2019)	C	U	V	IP	$\Sigma[w_1(\text{Dev})+w_2(\text{Late})+w_3(\text{Other})]$	CPLEX	Captured stochasticity in ship arrival times
Hu (2020)	C	D	F	MISOCP	Σ[(Late)+(Other)]	Epsilon-constraint method	Greenhouse gas emissions were captured
Li *et al.* (2020)	C	D	V	MIP	Σ(Wait+Hand)	Genetic-harmony search algorithm	Proposed a genetic-based harmony search method
Liu *et al.* (2020)	C	U	U	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Dev})+w_3(\text{Other})]$	HA	Built three two-stage models with robustness for less conservative solutions

Table 6: Continued

References	Spatial attribute	Ship arrivals	Handling times	Formulation types	Objective(s)	Solution approach	Special considerations
Luo *et al.* (2020)	C	D	F	MIP	$\Sigma[w_1(\text{Dev})+\Sigma w_2(\text{Late})]$	PSO	Ships moored in double lines
Wu and Miao (2020)	C	U	U	MIP	Σ(Other); Σ(Wait+Hand)	EA	Captured stochasticity in ship arrival and handling times
Yıldırım *et al.* (2020)	C	D	V	MIP	Σ[w(Wait)]	SO	Studied service priority and proposed a decision-making system
Al-Refaie and Abedalqader (2021)	C	D	F	MIP	Σ[(Wait)+(Hand)+w(Late)+(Other)]	LINGO	Evaluated customer satisfaction
Guo *et al.* (2021)	C	D	U	MIP	$\Sigma[w_1(\text{Hand})+w_2(\text{Late})]$	PSO	Uncertainty due to weather conditions was assessed
Park *et al.* (2021)	C	U	F	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Late})+w_3(\text{Dev})+w_4(\text{Other})]$	PSO	Introduced time buffers into the model
Wu and Miao (2021)	C	U	U	N/A	Σ(Late)	EA	Buffers were incorporated in baseline schedules
Agra and Rodrigues (2022)	C	D	U	MIP	Σ(Late)	Exact decomposition algorithm	Stochastic handling times were taken into consideration
Aslam *et al.* (2022a)	C	D	F	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Hand})+w_3(\text{Dev})+w_4(\text{Late})]$	CSA	The total service cost was minimized with a CSA
Aslam *et al.* (2022b)	C	D	F	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Hand})+w_3(\text{Dev})+w_4(\text{Late})]$	CSA	Comparison between CSA, EA, and CPLEX
Kolley *et al.* (2022)	C	U	F	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Dev})+w_3(\text{Late})]$	ML	Proposed four ML methods
Pérez-Cañedo *et al.* (2022)	C	U	U	MIP	Σ(Wait); Other	Lexicographic methods; epsilon-constraint method	Investigated a fuzzy problem with lexicographic methods
Samrout *et al.* (2022)	C	D	F	MIP	Σ[(Wait+Hand)+w(Late)]	EA	Container transshipment between berthing ships was investigated
Tang *et al.* (2022)	C	U	U	MIP	$\Sigma[w_1(\text{Wait})+w_2(\text{Dev})+w_3(\text{Other})]$	EA	Examined various interruptions from a proactive standpoint

Note. Exact optimization approaches: AMPL, CPLEX, epsilon-constraint method, exact decomposition algorithm, and LINGO. Heuristic approaches: HA. Metaheuristic approaches: AGWO, CSA, EA, genetic-harmony search algorithm, improved shuffled frog-leaping algorithm, PSO, and SA.

studies by ship arrival and handling times, objective components, mathematical formulations, and solution approaches are provided in Fig. 5.

3.2.3. *CBASP future research needs*

A number of research limitations were identified in the reviewed CBASP studies, which should receive more attention from the scientific community and practitioners in the following years. In particular, the following limitations were found to be the most common among the reviewed CBASP studies:

(i) Customer preferences and customer satisfaction have to be incorporated more consistently in the future CBASP efforts. The future CBASP studies should explicitly capture the level of customer satisfaction in the proposed mathematical formulations (Al-Refaie & Abedalqader, 2021; Dadashi *et al.*, 2017). High-priority customers should be provided effective service based on the agreements negotiated with MCT operators.

(ii) The majority of the reviewed CBASP studies assumed deterministic ship arrival and handling times. However, in reality, liner shipping and MCT operations are often impacted by various sources of uncertainties (e.g., adverse weather conditions, MCT congestion, equipment breakdowns, potential variations in handling productivity, etc.) (Agra & Rodrigues, 2022; Kolley *et al.*, 2022; Pérez-Cañedo *et al.*, 2022; Tang *et al.*, 2022). The future CBASP research efforts should concentrate on the development of effective analytical models for berth allocation and scheduling in the wake of uncertainties.

(iii) Machine learning techniques could be effective in prediction of ship arrival times (Kolley *et al.*, 2022). The future

Figure 5: Distribution of the reviewed CBASP studies by (a) ship arrival and handling times, (b) objective components, (c) mathematical formulations, and (d) solution approaches.

CBASP research efforts should focus on a more detailed evaluation of various ML methods (e.g., supervised learning, unsupervised learning, reinforcement learning, etc.) for prediction of ship arrival times using a large variety of datasets for a diverse group of geographical locations.

(iv) Certain ports around the globe are subject to the tidal effects, which cause variations in the depth of access channel and wharf. Larger ships may not be able to navigate at such ports during particular time periods. This imposes an additional operational constraint on the CBASP decisions. However, only a few studies directly incorporated potential impacts of tides in the proposed mathematical models (Dadashi *et al.*, 2017; Sheikholeslami & Ilati, 2018; Sheikholeslami *et al.*, 2014). Such a limitation should be addressed by the CBASP studies in the following years.

(v) The existing CBASP studies normally focus on the operational-level decisions. There is a lack of holistic optimization models that capture tactical and operational decisions simultaneously (Legato *et al.*, 2014; Lin *et al.*, 2018). The future CBASP efforts should focus on the development of holistic models that can incorporate tactical and operational decisions, as such models directly capture the interactions between different planning levels.

(vi) Some of the previous CBAP models were mainly developed for a short-term planning horizon (Yan *et al.*, 2019). More generalized and flexible optimization models, which can be applied for different planning periods, should be developed in the following years.

(vii) Emissions produced by ships when sailing at ports of call and during mooring can be reduced by means of collaborative strategies between MCT operators and shipping lines (Hu, 2020). The anticipated ship arrival time can be coordinated in a way that the arriving ship is not producing an excessive amount of emissions. Different collaborative strategies can be further studied in the future CBASP models to improve environmental sustainability.

(viii) Various ship service priority rules can be implemented in practice (Yıldırım *et al.*, 2020). The future CBASP studies should investigate the impacts of different ship service priority rules and determine the most promising ones based on the real-life MCT operational data.

3.3. Hybrid berth allocation and scheduling

The collected HBASP studies are further reviewed and summarized in this section. A total of eight studies were classified under the HBASP category. A representative optimization model for the hybrid dynamic berth allocation and scheduling problem (**HDBASP**) can be presented as follows (Imai *et al.*, 2007; Nishimura *et al.*, 2001).

The objective (27) of the **HDBASP** optimization model minimizes the total cost of berth allocation and scheduling in hybrid berthing settings, including the overall handling cost of ships, the

HDBASP: Hybrid dynamic berth allocation and scheduling problem

$$min[\sum_{s\in S}(\boldsymbol{HT}_s c_s^{HT}) + \sum_{s\in S}(\boldsymbol{WT}_s c_s^{WT}) + \sum_{s\in S}(\boldsymbol{LD}_s c_s^{LD})] \tag{27}$$

Subject to:

$$\sum_{b\in B}\boldsymbol{x}_{sb} = 1 \ \forall s\in S \tag{28}$$

$$L_b^{berth} - (\sum_{\underline{s}\in S:\underline{s}\neq\bar{s}} L_{\underline{s}}^{ship}\boldsymbol{y}_{\underline{s}\bar{s}}\boldsymbol{x}_{\underline{s}b} + L_{\bar{s}}^{ship})\boldsymbol{x}_{\bar{s}b} \geq 0 \ \forall \bar{s}\in S, b\in B \tag{29}$$

$$(D_b^{berth} - D_s^{ship})\boldsymbol{x}_{sb} \geq 0 \ \forall s\in S, b\in B \tag{30}$$

$$\boldsymbol{x}_{\underline{s}b}^{pos} + (L_{\underline{s}}^{ship}/2) \leq \boldsymbol{x}_{\bar{s}b}^{pos} - (L_{\bar{s}}^{ship}/2) - M(1-\boldsymbol{z}_{\underline{s}\bar{s}b}^{space}) \ \forall \underline{s},\bar{s}\in S, \underline{s}\neq\bar{s}, b\in B \tag{31}$$

$$\boldsymbol{ST}_{\underline{s}} + \boldsymbol{HT}_{\underline{s}} \leq \boldsymbol{ST}_{\bar{s}} - M(1-\boldsymbol{z}_{\underline{s}\bar{s}b}^{time}) \ \forall \underline{s},\bar{s}\in S, \underline{s}\neq\bar{s}, b\in B \tag{32}$$

$$\boldsymbol{z}_{\underline{s}\bar{s}b}^{space} + \boldsymbol{z}_{\underline{s}\bar{s}b}^{time} = 1 \ \forall \underline{s},\bar{s}\in S, \underline{s}\neq\bar{s}, b\in B \tag{33}$$

$$\boldsymbol{ST}_s \geq AT_s \ \forall s\in S \tag{34}$$

$$\boldsymbol{WT}_s \geq \boldsymbol{ST}_s - AT_s \ \forall s\in S \tag{35}$$

$$\boldsymbol{HT}_s = \sum_{b\in B}(HT_{sb}\boldsymbol{x}_{sb}) \ \forall s\in S \tag{36}$$

$$\boldsymbol{ET}_s \geq \boldsymbol{ST}_s + \boldsymbol{HT}_s \ \forall s\in S \tag{37}$$

$$\boldsymbol{LD}_s \geq \boldsymbol{ET}_s - RD_s \ \forall s\in S \tag{38}$$

$$\boldsymbol{x}_{sb}, \boldsymbol{y}_{\underline{s}\bar{s}}, \boldsymbol{z}_{\underline{s}\bar{s}b}^{space}, \boldsymbol{z}_{\underline{s}\bar{s}b}^{time} \in \mathbb{B} \ \forall \underline{s},\bar{s}\in S, \underline{s}\neq\bar{s}, \ b\in B \tag{39}$$

$$\boldsymbol{x}_{sb}^{pos}, \boldsymbol{ST}_s, \boldsymbol{ET}_s, \boldsymbol{WT}_s, \boldsymbol{LD}_s, \boldsymbol{HT}_s, AT_s, HT_{sb}, RD_s, L_s^{ship}, L_b^{berth}, D_s^{ship}, D_b^{berth}, c_s^{HT}, c_s^{WT}, c_s^{LD}, M \in \mathbb{R}^+ \ \forall s\in S, \ b\in B \tag{40}$$

overall waiting cost of ships, and the overall cost of late ship departures. Constraints (28) ensure that every arriving ship is scheduled for service at one of the berthing segments. Constraints (29) ensure that the length of ships assigned to a given berthing segment does not exceed the length of that berthing segment, considering the fact that some ships could be anchored next to each other at a given berthing segment. Constraints (30) indicate that the assigned berthing segment should have an adequate depth to service the given ship. Constraints (31) thorough (33) prevent the ship service overlaps in time and space dimensions for every berthing segment. Constraints (34) enforce the condition that the service of a given ship will start only after the arrival of that ship. Constraints (35) compute the waiting time of every ship arriving at the considered MCT. Constraints (36) compute the handling time of every ship arriving at the considered MCT. Constraints (37) compute the end service time of every ship arriving at the considered MCT. Constraints (38) compute the late departure time of every ship arriving at the considered MCT. Constraints (39) and (40) represent the integrality constraints of the parameters and variables of the **HDBASP** optimization model.

3.3.1. *Review of the collected HBASP studies*

Umang *et al.* (2017) investigated the HBASP considering potential deviations in ship arrival and handling times from the original berthing schedule. The objective was to reduce the schedule recovery cost. A smart greedy algorithm and an optimization-based recovery approach were suggested in order to address the developed mathematical formulation. Issam *et al.* (2018) presented a bat-inspired metaheuristic for berth allocation and scheduling at MCTs with a hybrid berthing layout. The computational experiments were conducted based on the data collected for the Tangier container terminal (Morocco). It was found that the proposed algorithm outperformed other alternative methods in terms of the total turnaround time of incoming ships. Kovač *et al.* (2018) presented an HDBASP optimization model aiming to minimize the deviation between the actual and scheduled berthing positions for the arriving ships, waiting time, and late departures. The authors designed four different versions of variable neighborhood search (VNS). The numerical experiments demonstrated promising performance of the proposed metaheuristic methods.

Hammouti *et al.* (2019) presented a modified sailfish optimizer metaheuristic algorithm to optimize operations at MCTs with a hybrid berthing layout. The objective function of the proposed optimization model aimed to minimize the total turnaround time of ships calling at the MCT. Based on the conducted computational experiments, it was found that the developed metaheuristic was able to discover competitive solutions within shorter computational time when comparing to the alternative solution methods. Zhang *et al.* (2019) investigated berth allocation and scheduling at MCTs with an indented berthing layout, which is recognized as a special case of a hybrid berthing layout. Two strategies for berth allocation and scheduling were presented: (i) the separate strategy allowing indented berths to serve only large ships and marginal berths to serve only small ships; and (ii) the integrated strategy allowing indented and marginal berths to serve large and small ships. The proposed strategies were evaluated using an EA-based metaheuristic. It was found that the integrated strategy could provide more effective ship service than the separate strategy. Jia *et al.* (2020) proposed a SO approach for an MCT with a hybrid berthing layout, where two types of ships were served (i.e., deep-sea ships and feeder ships). The handling times of feeder ships were assumed to be uncertain due to the lack of information interchange between feeder operators and MCT operators. The performance of the proposed methodology was evaluated using the realistic operational data collected from a container terminal in Shanghai, China.

Wawrzyniak *et al.* (2020) investigated a decision program of selecting appropriate solution algorithms for berth allocation and scheduling under computational runtime limits. Consideration of computational time limits is essential, since the BAP models must be solved many times at the strategic port capacity planning level. The study proposed a novel approach for the algorithm portfolio selection. The portfolio selection was based on the algorithmic performance for the pre-determined set of training problem instances. The algorithmic performance was assessed based on solution quality obtained and computational time incurred. A portfolio of efficient heuristics was proposed to solve large-scale HDBASP instances for different planning horizons. Lu *et al.* (2022) investigated the balance between berth utilization and handling efficiency at MCTs with a hybrid berthing layout. An optimization model was developed to minimize the total turnaround time of ships arriving for service at the MCT. A custom EA-based solution algorithm was developed to solve the resulting mathematical model. The developed EA algorithm was compared against CPLEX, SA, and TS and was found to be superior in terms of quality of obtained solutions. Furthermore, the proposed algorithm demonstrated acceptable performance in terms of computational time.

3.3.2. *Summary of the HBASP literature*

Table 7 presents a detailed summary of findings that were revealed after the review of collected HBASP studies. In particular, the table showcases a concise summary of berth spatial attributes, ship arrival classifications, handling time types, formulation types, objective components considered, adopted solution approaches, and special HBASP considerations. It can be observed that a significant number of HBASP studies considered dynamic ship arrivals and variable handling times (a total of 50.0% of studies). A total of 25.0% of the HBASP studies modeled dynamic ship arrivals and fixed handling times. Furthermore, ship waiting and handling times were found to be the most popular components of the objective functions used in the proposed HBASP mathematical models. MIP formulations were identified to be the most common types of formulations for the HBASP mathematical models. Metaheuristic algorithms were found to be the most popular solution methods that were deployed to solve the HBASP decision problems. Wawrzyniak *et al.* (2020) presented a methodology for developing a portfolio of algorithms for the HBASP instead of just one solution approach. Distributions of the reviewed HBASP studies by ship arrival and handling times, objective components, mathematical formulations, and solution approaches are provided in Fig. 6.

3.3.3. *HBASP future research needs*

A number of research limitations were identified in the reviewed HBASP studies, which should receive more attention from the scientific community and practitioners in the following years. In particular, the following limitations were found to be the most common among the reviewed HBASP studies:

(i) Robust mathematical formulations are necessary to incorporate the effects of disruptions that occur during the ship berthing and handling periods. More effective approaches for the prediction of uncertain parameters related to sailing, mooring, and operating stages should be deployed in the following years to improve the robustness of HBASP decisions (Jia *et al.*, 2020; Umang *et al.*, 2017).

(ii) Penalties for late ship departures were considered by a number of HBASP studies (Jia *et al.*, 2020; Umang *et al.*, 2017). Various pricing policies should be investigated systematically as a part of the future HBASP research efforts to reach the balance between service cost and daily operational efficiency (Umang *et al.*, 2017).

(iii) New HBASP mathematical formulations should be explored to explicitly capture customer satisfaction. Zhang *et al.* (2019) modeled customer satisfaction using a function penalizing ship waiting times. More comprehensive functions for customer satisfaction should be investigated by the future HBASP research efforts.

(iv) Only a limited number of HBASP studies focused on modeling of an indented berthing layout, which could be promising for serving large container ships (Zhang *et al.*, 2019). Indented berthing positions could be implemented in different ways (e.g., some positions can be specifically allocated for the service of large container ships and other positions could serve small and large ships). The future HBASP studies should investigate the potential of indented berthing positions and provide constructive recommendations on their use under different scenarios.

(v) A channel berthing layout, where ships could be served along the channel from both sides of the channel, can be effective for MCTs handling small- and large-size ships (Imai *et al.*, 2013). However, the channel berthing layout has not been studied by the recent HBASP studies. This limitation should be addressed in the following years.

4. Addressing the Need for More Effective Solution Approaches

Some of the critical research limitations identified in the reviewed BASP studies were discussed in Sections 3.1.3–3.3.3 mostly focusing on the operational aspects of berth allocation and scheduling. Along with the aforementioned future research needs, the future BASP studies should concentrate on addressing the needs for more effective solution approaches. Such needs can be justified by the computational complexity of different BASP variants. In particular, most of the BASP variants can be reduced to the unrelated machine scheduling problem, where the arriving jobs have to be allocated for processing among the available machines, and the processing time normally depends on the specific characteristics of jobs and machines. Similarly, most of the BASP variants aim to allocate the incoming ships among the available berthing positions, and the ship processing time (i.e., handing time) may vary from one berthing position to another. The unrelated machine scheduling problem is known to have an NP-hard computational complexity and has a large search space for realistic-size problem instances. Therefore, more effective solution approaches and techniques should be further investigated for different BASP variants, as discussed throughout this section of the manuscript.

First, random solution initialization approaches are common for heuristics and metaheuristics. The BASP decision problem has its specific features, which should be directly considered when developing solution initialization procedures. The FCFS policy, where ships are assigned to the berthing positions based on the order of their arrival, has been used by some of the previous BASP efforts (Dulebenets, 2017a, b; Kavoosi *et al.*, 2019b). More intelligent approaches for solution initialization should be investigated in the following years. Second, new types of algorithms should be investigated and applied for berth allocation and scheduling. The previous research efforts offered a large variety of innovative metaheuristic-based algorithms for different decision problems, including the lion optimization algorithm, dragonfly algorithm, grasshopper optimization algorithm, multi-verse optimizer, sine cosine algorithm, social engineering optimizer, salp-swarm algorithm, whale optimization algorithm, and others (Abbaspour *et al.*, 2022; Azadeh *et al.*, 2016; Cheng *et al.*, 2021; Fazli *et al.*, 2019; Gharib *et al.*, 2022; Tian *et al.*, 2023a, b; Yazdani & Jolai, 2016). The aforementioned algorithms were found to be effective for different decision problems. However, their potential still has to be investigated for the BASP by the future studies. The need for exploring the potential of different innovative metaheuristic-based algorithms can be also justified by the no-free-lunch theorem (i.e., there is no guarantee that a given metaheuristic will show competitive performance for the BASP and its different variants).

Third, metaheuristic algorithms in their standard forms may not be effective for certain decision problems. Problem-specific

Table 7: Summary of findings: HBASP.

Reference	Spatial attribute	Ship arrivals	Handling times	Formulation types	Objective(s)	Solution approach	Special considerations
Umang *et al.* (2017)	H	U	U	MIP	$\Sigma[w_1(\text{Dev})+ w_2(\text{Late})]$	Optimization-based recovery algorithm; smart greedy algorithm	The greedy algorithm and set partitioning method were utilized for the berth schedule recovery
Issam *et al.* (2018)	H	D	V	MIP	$\Sigma[w_1(\text{Wait})+ w_2(\text{Hand})]$	Bat-inspired algorithm	A bat-inspired metaheuristic was proposed
Kovač *et al.* (2018)	H	D	F	MIP	$\Sigma[w_1(\text{Dev})+w_2(\text{Wait})+ w_3(\text{Late})]$	VNS	Four variations of the VNS metaheuristic were developed
Hammouti *et al.* (2019)	H	D	V	MIP	$\Sigma(\text{Wait+Hand})$	Modified sailfish optimizer	Congestion was found to be the primary issue that interfered with the MCT operations
Zhang *et al.* (2019)	H	D	V	MIP	$\Sigma[(\text{Hand+Wait})+ w(\text{Other})]$	EA	Different strategies at the MCT with an indented berthing layout were studied
Jia *et al.* (2020)	H	D	U	MINLP	$\Sigma[w_1(\text{Late})+w_2(\text{Dev})]$	SO	Minimized late departures and feeder ship displacement
Wawrzyniak *et al.* (2020)	H	D	F	N/A	$\Sigma[w(\text{Wait+Hand})]$	Portfolio of algorithms	Proposed a method for selecting portfolios of algorithms
Lu *et al.* (2022)	H	D	V	MIP	$\Sigma(\text{Wait+Hand})$	EA	The service efficiency and resource utilization were balanced

Note. Heuristic approaches: smart greedy algorithm. Metaheuristic approaches: bat-inspired algorithm, EA, modified sailfish optimizer, and VNS.

hybridization techniques (e.g., local search heuristics and exact optimization procedures) can substantially improve the performance of metaheuristics and enhance the quality of solutions at convergence (El-Shorbagy & El-Refaey, 2022; Li *et al.*, 2022; Morasaei *et al.*, 2022; Rizk-Allah, 2018). Although some recent BASP studies offered various hybrid algorithms (Barbosa *et al.*, 2019; Kavoosi *et al.*, 2019b; Mohammadi & Forghani, 2018), more research is needed to develop advanced types of hybridization based on the specific properties of the BASP decision problem. Fourth, the future BASP studies could explore different forms of parallel metaheuristic algorithms. Parallelization can assist with a more effective way of exploring the available domains of the search space and prevent potential premature convergence. Generally, there are three standard approaches for parallelization of metaheuristics, such as the master-slave framework, island framework, and diffusion framework (Alba & Tomassini, 2002; Lewis *et al.*, 2009; Tomassini, 2005). Based on the master-slave framework, the computational tasks are divided between the master and its slaves, so these tasks can be tackled simultaneously. The island framework allocates the available solutions to different islands. The solutions interact with each other on each island, and the islands periodically exchange some of the solutions after a predetermined number of generations. Based on the diffusion framework, the available solutions are placed within a diffusion grid, and only neighbors are permitted to interact with each other. A very limited number of recent BASP studies explored the potential of various parallelization techniques (Dulebenets, 2020; Kavoosi *et al.*, 2019a), and this area can be explored more in depth in the following years.

Fifth, simheuristics and hyperheuristics are becoming increasingly popular in different domains (Juan *et al.*, 2015; Wang *et al.*, 2020; Yazdani *et al.*, 2021). Simheuristics can be effective in capturing various sources of uncertainty in a natural way by integrating a simulation model within a metaheuristic framework. Hyperheuristics offer more flexibility when comparing to traditional metaheuristics, as hyperheuristics can update search operators dynamically throughout the algorithmic evolution based on certain criteria. The future research efforts should concentrate on assessing the performance of innovative simheuristic- and hyperheuristic-based algorithms for different variations of the BASP decision problem. Sixth, Wawrzyniak *et al.* (2020) conducted an interesting study and proposed a portfolio of algorithms for the HDBASP. Different types of algorithms were considered for the portfolio, including greedy algorithms, hill climbers, greedy randomized adaptive search procedure-based methods, and iterated local search-based methods. The future BASP studies could extend the portfolio of algorithms and include other advanced optimization approaches (e.g., hybrid algorithms, island algorithms, diffused algorithms, simheuristics, and hyperheuristics). It is essential to concentrate on the aforementioned future research needs and explore more effective solution approaches for different BASP variations.

5. Conclusions

MCTs are essential for international trade networks and global market. MCT operators must address the operational challenges with appropriate analytical methods to meet the needs of the

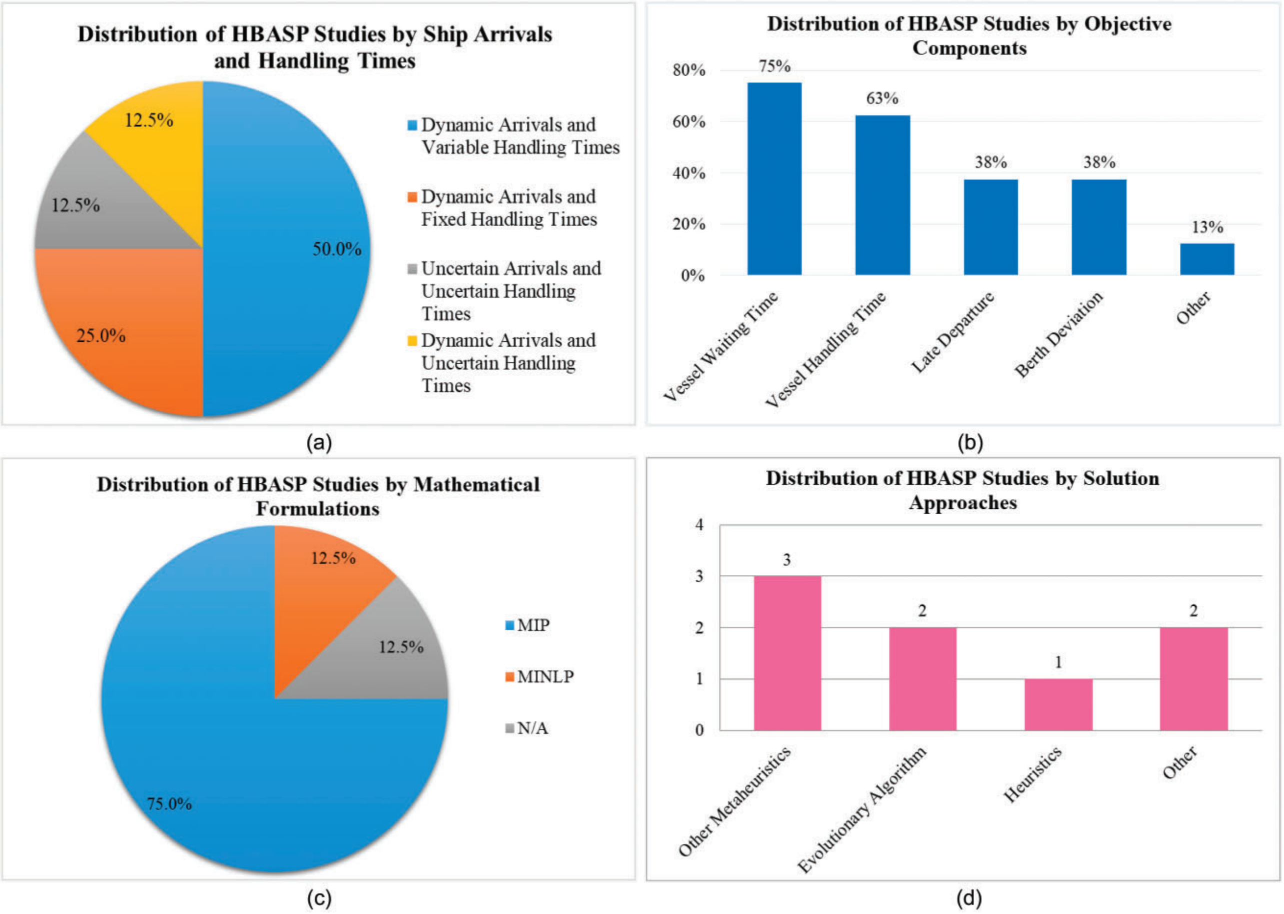

Figure 6: Distribution of the reviewed HBASP studies by (a) ship arrival and handling times, (b) objective components, (c) mathematical formulations, and (d) solution approaches.

market and cope with the rapid growth in trade volumes. BASP, aiming to assign the arriving ships to the available berthing positions and determine the ship service order at each position, is one of the important decisions faced by terminal operators during operations planning. An optimal and robust berth schedule remarkably improves the productivity and competitiveness of a seaport. A significant number of berth allocation and scheduling studies have been conducted over the last years. Thus, there is a need for a comprehensive and critical literature survey to analyze the state-of-the-art research progress, developing tendencies, current shortcomings, and potential future research directions. Therefore, this manuscript thoroughly selected scientific studies dedicated to the BASP that were not reviewed in the former survey study by Bierwirth and Meisel (2015). The identified 94 studies were classified based on the adopted berthing layout (i.e., DBASPs, CBASPs, and HBASPs) and were systematically reviewed. A representative mathematical formulation for each category was presented, following by a detailed summary of various considerations and characteristics of every study.

It was found that a multitude of mathematical models had been developed for berth allocation and scheduling over the past years, including MIP, integer programming, and MINLP models. The established mathematical formulations featured a wide range of various objective functions (e.g., minimize the total turnaround time of ships, minimize the ship waiting time, minimize the late departures of ships, minimize the ship handling time, minimize the deviation from preferred berthing position, minimize the energy usage, minimize the pollution emissions, minimize the total turnaround cost, among others). Various solution approaches were adopted by researchers to address the proposed models, including evolutionary computation, HAs, metaheuristics (e.g., SA, PSO, ant colony optimization, BCO, SFA, and Levy flight-based metaheuristic), exact optimization approaches (CPLEX, LINGO, AMPL, and B&B), and other methods. A number of special considerations were integrated by several studies, such as tidal window constraints, daytime operation preferences, service priority, spatial considerations, and emission of pollutants.

Along with the future research needs related to the operational aspects of berth allocation and scheduling, several critical research needs were identified with respect to more effective solution approaches, including the following; (i) development of more intelligent approaches for solution initialization, (ii) deployment of recent metaheuristic-based algorithms, (iii) design of advanced types of hybridization based on the problem-specific properties, (iv) application of various parallelization techniques for solution algorithms, (v) deployment of simheuristics and hyperheuristics for berth allocation and scheduling, and (vi) design of new portfolios of algorithms for effective and timely berth allocation and scheduling decisions. Addressing the identified future research needs is anticipated to facilitate planning of MCT operations, prevent potential delays in ship service, and, ultimately, assist with timely deliveries of cargoes to the designated customers.

Although some important insights and tendencies were identified by the present survey study, it could be expanded further as a part of the future research. First, a set of constructive consultations can be conducted with the maritime industry professionals and experts to determine the critical operational constraints and considerations they account for during operations planning. These operational constraints and considerations should be explicitly modeled by the future studies on berth allocation and scheduling. Second, the collected studies were primarily classified based on the adopted berthing layout. More complex and comprehensive sub-classifications can be used in the future (e.g., the studies modeling indented berthing layout, the studies modeling the channel berthing layout, the studies modeling tidal time window constraints, the studies with deterministic settings versus the studies with stochastic settings, etc.). Representative mathematical formulations could be developed for all the study groups. Third, a separate survey study could be conducted with a specific focus on solution approaches for berth allocation and scheduling. The present survey provided a holistic high-level overview of the solution approaches proposed for berth allocation and scheduling. More detailed and concentrated review of the algorithms (e.g., description of various algorithmic operators, presentation of pseudo-codes, and review of convergence criteria) could be conducted by the future studies. Fourth, the present survey study specifically focused on berth allocation and scheduling. Other decision problems at MCTs (e.g., quay crane allocation and scheduling, internal transport vehicle deployment, yard crane allocation and scheduling, drayage truck scheduling, and integrated decision problems) could be further investigated by the future studies.

Conflict of interest statement

None declared.

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Appendix 1.

Notations Used in the Representative Optimization Models

Table A1. Notations used in the **DDBASP** optimization model.

Component	Description
Sets	
$S = \{1, \ldots, n^1\}$	Set of arriving ships that will be serviced at the MCT
$B = \{1, \ldots, n^2\}$	Set of berthing segments (or berths) at the MCT
$O = \{1, \ldots, n^3\}$	Set of ship service orders
Decision variables	
$\mathbf{x}_{sbo},\ s \in S,\ b \in B, o \in O$	=1 If ship s is serviced as oth ship at berthing segment b (else =0)
Auxiliary variables	
$\mathbf{y}_{sbo},\ s \in S,\ b \in B, o \in O$	Idling time of berthing segment b between the service start of ship s and the departure time of its immediately preceding ship serviced in the $(o-1)$th order (hours)
$\mathbf{ST}_s,\ s \in S$	Start time of service for ship s (hours)
$\mathbf{ET}_s,\ s \in S$	End time of service for ship s (hours)
$\mathbf{WT}_s,\ s \in S$	Waiting time before service for ship s (hours)
$\mathbf{LD}_s,\ s \in S$	Late departure time for ship s (hours)
Parameters	
$BA_b,\ b \in B$	Time when berthing segment b becomes available for service for the first time in the considered planning period (hours)
$AT_s,\ s \in S$	Anticipated time of arrival for ship s (hours)
$HT_{sb},\ s \in S,\ b \in B$	Handling time for ship s at berthing segment b (hours)
$RD_s,\ s \in S$	Requested time of departure for ship s (hours)
$L_s^{\text{ship}}, s \in S$	Length of ship s including the required safety distance (meters)
$L_b^{\text{berth}}, b \in B$	Length of berthing segment b (meters)
$D_s^{\text{ship}}, s \in S$	Draft of ship s including the required safety distance (meters)
$D_b^{\text{berth}}, b \in B$	Depth of berthing segment b (meters)
$c_s^{HT},\ s \in S$	Handling cost for ship s (USD/hour)
$c_s^{WT},\ s \in S$	Waiting cost for ship s (USD/hour)
$c_s^{LD},\ s \in S$	Late departure cost for ship s (USD/hour)
M	Sufficiently large positive number

Table A2. Notations used in the **CDBASP** optimization model.

Component	Description
Sets	
$S = \{1, \ldots, n^1\}$	Set of arriving ships that will be serviced at the MCT
Decision variables	
$\mathbf{x}_s^{\text{pos}},\ s \in S$	Berthing position for ship s (meters)
Auxiliary variables	
$\mathbf{ST}_s,\ s \in S$	Start time of service for ship s (hours)
$\mathbf{ET}_s,\ s \in S$	End time of service for ship s (hours)
$\mathbf{WT}_s,\ s \in S$	Waiting time before service for ship s (hours)
$\mathbf{LD}_s,\ s \in S$	Late departure time for ship s (hours)
$\mathbf{HT}_s,\ s \in S$	Handling time for ship s (hours)
$\mathbf{z}_{\underline{s}\bar{s}}^{space}, \underline{s}, \bar{s} \in S, \underline{s} \neq \bar{s}$	=1 If ship $\underline{s}$ is positioned to the left side of ship $\bar{s}$ along the wharf (else =0)
$\mathbf{z}_{\underline{s}\bar{s}}^{time}, \underline{s}, \bar{s} \in S, \underline{s} \neq \bar{s}$	=1 If ship $\underline{s}$ is serviced before ship $\bar{s}$ (else =0)
Parameters	
$AT_s,\ s \in S$	Anticipated time of arrival for ship s (hours)
$HT_s^{\text{pref}},\ s \in S$	Handling time for ship s at the preferred berthing position (hours)
$RD_s,\ s \in S$	Requested time of departure for ship s (hours)
$L_s^{\text{ship}}, s \in S$	Length of ship s including the required safety distance (meters)
L^{wharf}	Length of wharf (meters)
$D_s^{\text{ship}}, s \in S$	Draft of ship s including the required safety distance (meters)
$D_s^{\text{wharf}}, s \in S$	Depth of the berthing segment where ship s is moored (meters)
$x_s^{\text{pref}},\ s \in S$	Preferred berthing position for ship s (meters)
$\alpha_s,\ s \in S$	Ratio of increasing handling time due to the deviation from preferred berthing position for ship s
$c_s^{HT},\ s \in S$	Handling cost for ship s (USD/hour)
$c_s^{WT},\ s \in S$	Waiting cost for ship s (USD/hour)
$c_s^{LD},\ s \in S$	Late departure cost for ship s (USD/hour)
M	Sufficiently large positive number

Table A3. Notations used in the **HDBASP** optimization model.

Component	Description
Sets	
$S = \{1, \ldots, n^1\}$	Set of arriving ships that will be serviced at the MCT
$B = \{1, \ldots, n^2\}$	Set of berthing segments (or berths) at the MCT
Decision variables	
$\mathbf{x}_{sb},\ s \in S,\ b \in B$	=1 If ship s is serviced at berthing segment b (else =0)
$\mathbf{x}_{sb}^{\mathrm{pos}},\ s \in S,\ b \in B$	Berthing position for ship s at berthing segment b (meters)
Auxiliary variables	
$\mathbf{ST}_s,\ s \in S$	Start time of service for ship s (hours)
$\mathbf{ET}_s,\ s \in S$	End time of service for ship s (hours)
$\mathbf{WT}_s,\ s \in S$	Waiting time before service for ship s (hours)
$\mathbf{LD}_s,\ s \in S$	Late departure time for ship s (hours)
$\mathbf{HT}_s,\ s \in S$	Handling time for ship s (hours)
$\mathbf{y}_{\underline{s}\bar{s}}, \underline{s}, \bar{s} \in S, \underline{s} \neq \bar{s}$	=1 If ship $\bar{s}$ starts its service when ship $\underline{s}$ is being serviced at the same berthing segment (else =0)
$\mathbf{z}_{\underline{s}\bar{s}b}^{space}, \underline{s}, \bar{s} \in S, \underline{s} \neq \bar{s}, b \in B$	=1 If ship $\underline{s}$ is positioned to the left side of ship $\bar{s}$ along berthing segment b (else =0)
$\mathbf{z}_{\underline{s}\bar{s}b}^{time}, \underline{s}, \bar{s} \in S, \underline{s} \neq \bar{s}, b \in B$	=1 If ship $\underline{s}$ is serviced before ship $\bar{s}$ at berthing segment b (else =0)
Parameters	
$AT_s,\ s \in S$	Anticipated time of arrival for ship s (hours)
$HT_{sb},\ s \in S,\ b \in B$	Handling time for ship s at berthing segment b (hours)
$RD_s,\ s \in S$	Requested time of departure for ship s (hours)
$L_s^{\mathrm{ship}}, s \in S$	Length of ship s including the required safety distance (meters)
$L_b^{\mathrm{berth}}, b \in B$	Length of berthing segment b (meters)
$D_s^{\mathrm{ship}}, s \in S$	Draft of ship s including the required safety distance (meters)
$D_b^{\mathrm{berth}}, b \in B$	Depth of berthing segment b (meters)
$c_s^{HT},\ s \in S$	Handling cost for ship s (USD/hour)
$c_s^{WT},\ s \in S$	Waiting cost for ship s (USD/hour)
$c_s^{LD},\ s \in S$	Late departure cost for ship s (USD/hour)
M	Sufficiently large positive number

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